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CHARACTER AND DEPTH OF OXIDATION OF THE REACTIVE ACID TAILINGS AT THE WAITE AMULET MINESITE, NORANDA, QUEBEC

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ABSTRACT

Microscopic examination of 82 polished sections from 69 core samples of the Waite Amulet tailings pile has shown that alteration intensity consistently decreases with increasing depth. The near-surface zone is strongly oxidized, as is indicated by the destruction of almost all pyrite and pyrrhotite, but the relative immaturity of gossan development is evident from the absence of a significant leached zone, the retention of iron oxyhydroxides as pseudomorphs of sulphides, and the lack of hardpan in the core samples. Iron released from the oxidation of sulphides is incorporated mainly in goethite, lepidocrocite, ferrihydrite, and jarosite, whereas sulphate is precipitated mainly as gypsum crystals and jarosite. Beneath the upper oxidized part of the tailings is an intermediate zone of weak alteration which is succeeded downward by a zone of negligible sulphide alteration. Gypsum occurs throughout the tailings pile, but is generally most abundant in, and near, strongly oxidized material. Iron in the water-soluble fraction of the tailings typically is concentrated in the upper part of the intermediate zone, and jarosite abundance closely follows the vertical profiles for microscopically determined alteration intensity.

Keywords: tailings, sulphides, alteration, oxidation, depth profiles, Waite Amulet, Quebec.

CARACTÈRE ET INTENSITÉ DE L'OXYDATION DES RÉSIDUS ACIDES RÉACTIFS QUI SE TROUVENT SUR L'EMPLACEMENT DE LA MINE WAITE AMULET, À NORANDA (QUÉBEC)

par

J.L. Jambor

RÉSUMÉ

Un examen microscopique de 82 sections polies de 69 échantillons carottés provenant de l'amas de résidus sur l'emplacement de Waite Amulet a révélé que l'intensité de l'altération diminue en fonction de la profondeur. La destruction de la plus grande partie de la pyrite et de la pyrrhotite dans la zone près de la surface révèle que celle-ci est fortement oxydée. Cependant, l'absence d'une zone de lessivage importante, la rétention d'oxydes de fer hydratés comme pseudomorphes des minéraux sulfurés et l'absence de cuirasse ferrugineuse que dénotent les échantillons carottés indiquent que le développement du chapeau ferrugineux est relativement prématuré. Le fer libéré par l'oxydation des sulfates est incorporé principalement dans la goéthite, lépidocrocite, ferrihydrite et jarosite tandis que le sulfate est en grande partie précipité sous forme de cristaux de gypse et de jarosite. Au-dessous de la couche oxydée supérieure de résidus se trouve une zone intermédiaire faiblement altérée suivie d'une zone qui a été très peu altérée par les sulfates. Le gypse est présent dans tout l'amas de résidus, mais se retrouve en plus grande quantité dans les matériaux fortement oxydés ou à proximité de ceux-ci. Le fer contenu dans la fraction des résidus qui est soluble dans l'eau est concentré d'une manière typique dans la partie supérieure de la zone intermédiaire. L'abondance de la jarosite suit de près les profils verticaux de l'intensité de l'altération qui ont été déterminés au microscope.

INTRODUCTION

The Waite Amulet minesite near Noranda, Quebec (Fig. 1) contains about 5.9 million tonnes of sulphide-rich tailings in an elevated 41 hectare dam. The tailings are 2 to 15 m thick, and were accumulated as the wastes from 10 orebodies mined during the interval 1929-1962. The tailings and site are undergoing detailed hydrogeochemical studies as part of the RATS program (Reactive Acid Tailings Study). Noranda Research Centre and CANMET are joint participants in the Waite Amulet study.

As part of the Waite Amulet investigation, nine holes were cored through the tailings pile in 1985. Core samples from hole WA-20 were examined mineralogically by Petruk and Pinard (1986), and their image analysis study provided quantitative abundances of the tailings minerals and alteration products that occur in one vertical section through the tailings pile. Because the alteration products are complex and extremely fine-grained mixtures that are difficult to identify as specific mineral phases, a detailed mineralogical study of core WA-20 also was done by Jambor (1986), who used mainly optical microscopy and X-ray powder-diffraction methods to characterize the phases. As well, chemical analyses of bulk samples were used to estimate the abundances of specific alteration minerals that had been identified by the microscopic and X-ray techniques.

Hole WA-20 is located on a bench along the western side of the tailings pile (Fig. 1,4) and therefore is not representative of the hydrogeological environment that applies to the bulk of the pile. To obtain a better indication of the character of the tailings existing in saturated conditions, an additional 31 core samples selected from piezometric sites were examined

mineralogically and chemically (Jambor 1987). The study showed the cores to be unaltered, as was indicated by the negligible amounts of altered sulphides. As a consequence of these earlier studies, it was concluded that microscopic examination of polished sections of the tailings is, by itself, a viable method of discriminating between altered and unaltered samples. Therefore, the need for chemical analyses of tailings samples that are in an observably pristine, unaltered condition, can be reduced substantially. On this basis, to further evaluate mineralogical conditions in the near-surface, unsaturated zone, it was agreed that an additional 72 core samples would be examined in polished section to establish the relative degree of alteration in each sample; the assumption was that a significant number of samples would be in a relatively unaltered state. The identification of pristine samples is in itself extremely useful information, but the immediate, practical concern was the need to reduce the number of samples that would require more thorough mineralogical and chemical studies.

SAMPLES AND SAMPLE SITES

The core samples are from 6 holes which, together with WA-20, represent two vertical cross-sections approximately along the length and width of the tailings pile (Fig. 2). The number of cores from each hole ranged from 6 (hole WA-2) to 18 (hole WA-1). As in the study of the cores from the piezometric sites (Jambor 1987), the as-received cores were wrapped in labelled plastic bags and the cores were in a frozen state. The samples were stored in a freezer at CANMET until the thawing and drying operations began.

The as-received samples consisted of half of the original core and aluminum core barrel, the split having been achieved by lengthwise band-saw

cutting of the frozen core and encapsulating barrel. On each barrel was marked the borehole and sample numbers, and the upward (toward surface) direction was indicated by an arrow.

SAMPLE PREPARATION

The frozen core was separated from its aluminum casing, which was discarded, and each core was placed in a separate, labelled white box and allowed to thaw at room temperature. The colour of the boxes proved to be important as an evidently sensitive indicator of acidic reaction from the excess moisture in the cores. Care also was taken to orient the cores in a consistent downhole direction, thereby ensuring that the observed oxidation profiles were placed in their appropriate positions.

The room-temperature drying, sieving, and blending of each core sample followed the procedures outlined previously (Jambor 1986) and need not be repeated in detail. As before, the tailings were screened to minus 36 mesh (aperture size 425 micrometres) and various splits and reference samples were selected before and after screening. Prior to screening, a few of the cores were partitioned into sub-samples that preserved special features; for example, where part of a core consisted of ocherous, strongly oxidized tailings in relatively sharp contact with black, sulphide-rich core, an effort was made to divide the core into two representative fractions.

In order to minimize the dissolution of water-soluble phases, all of the polished sections were prepared using non-aqueous media. For the polished sections, the -36 mesh samples were rescreened to -270 mesh (aperture size 53 micrometres) and the fines were rejected. Although 72 cores were received

initially, 3 of the organic-bearing, clay-rich surface samples were not examined in polished sections. Because of the sub-sampling of some cores, however, 82 polished sections were prepared from the remaining 69 cores, and 81 separate samples were available for chemical analyses.

Contamination

Except for the removal of large, coherent pieces of organic material such as pine needles and well-preserved twigs, the standard procedure in sample preparation was to crush and screen the complete sample or sub-sample (excluding small portions which were retained as coarse reference material). Two samples from hole WA-8 were treated differently, however, because they contained an obvious contamination that was removed readily. These samples, C-5 and C-6, consist of black, sulphide-rich tailings beneath the strongly oxidized, ocherous, near-surface cap. The C-5 and C-6 sulphide-rich cores each contained a thin rim of ocherous material only at the interface of the core barrel and main core, thereby indicating that the ocherous rind was a contaminant from the up-hole, oxidized zone. The contaminant was removed from the frozen core by using a water spray. Only in these two cores was the contamination so pronounced and so accessible, and no other cores were treated in this manner.

Acid losses

As was done in the study of the cores from the piezometric sites (Jambor 1987), the thawing and initial drying of the cores occurred in shallow boxes of thin, white cardboard. Only with the present series of samples was a reaction with the cardboard observed: for several samples the moist base of the box eventually turned brown, whereas other samples showed no effect. The browning of the cardboard indicates that an acidic reaction had occurred, and

thus there was some loss of water-soluble sulphate. That the sulphate losses were probably small was inferred from the absence of visible precipitates. Nevertheless, as a check the remaining halves of cores C-8, C-9, and C-10 (hole WA-8), which had been retained in a frozen state at Noranda Research Centre, were again sawn in half and a split of each was shipped to CANMET. One split of each sample, comprising one-quarter of the original core, was received in a frozen state and was air-dried and sieved in the normal manner, except that the drying was done in plastic-lined trays. Table 1 lists all of the cores from which the acidic, browning effects were observed, and Table 2 gives a comparison of the soluble-sulphate results obtained for cores WA-8, C-8 to C-10. Unfortunately, the 3 sets of samples do not show a consistent trend: in 2 of the pairs (C-9 and C-10), increases in pH but losses of some sulphate are indicated. In contrast, in the C-8 pair the pH and analytical SO_4 are higher in the original sample than in the quarter split. New analyses of the C-8 sample, done in duplicate, confirmed the high sulphate obtained in the original analysis. Consequently, although no definitive conclusions can be made, it seems likely that the amount of acid lost in the original drying procedure was not appreciable.

MEGASCOPIC CHARACTER OF CORES

Unlike the cores from the piezometric sites, the samples from each borehole in the present series include a well-defined oxidized zone near the beginning of the sample sequence (Fig. 5). The initial sample (C-1) from each hole also contains clay, soil, or abundant organic matter, and it thus is assumed that the consecutively numbered sample sequence for each hole represents a vertical profile from surface to progressively increasing, but unspecified depths.

Although none of the cores from the piezometric sites contained strongly oxidized zones, a few thin, weakly oxidized "iron-stained" layers were noted to occur erratically. These weakly oxidized layers were interpreted to be minor paleosurfaces at which local oxidation occurred during interruptions in the accumulation of the tailings pile. The same type of local oxidation is present in a few of the current series of cores, but the paleosurface origin of the alteration is clearly evident from the concentrations of vegetation in, or at the contacts, of some of the oxidized layers.

Table 3 summarizes the general megascopic features of the cores from each drillhole. Each of the holes shows a strongly oxidized, sulphide-depleted near-surface zone which progresses downward to a sulphide-rich zone. Colour is a good indicator of this progression, the change being from shades of yellow or brownish yellow, to black. Also evident in Table 3 is that the clay-rich surface samples intersected in holes WA-8 and WA-1 are carbonate-rich, a feature which presumably is the manifestation of lime addition to the tailings surface. By contrast, surface or near-surface cores that lack a clay-rich zone do not contain carbonates. Regardless of whether a lime-rich surface is present or absent, the strongly oxidized upper parts of all holes contain abundant crystals of gypsum that occur as clear, disseminated euhedra, typically 0.5 to 1.0 mm long.

In addition to the gypsum euhedra, whose size and quantity indicate in-situ crystallization in the tailings, small amounts of sulphates were deposited from the aqueous phase contained in the as-received cores. These precipitates consist of fine-grained, fibrous, radiating aggregates of gypsum (Fig. 6), and more-copious ferrohexahydrite, $FeSO_4.6H_2O$. The latter forms sparse white blooms that consist of thin coatings, beads, and filiform aggregates on sulphide-rich samples (Fig. 7).

MICROSCOPIC CHARACTERIZATION

Alteration of the Waite Amulet tailings is generally intense near surface, but this intensity nevertheless is only at moderate levels relative to alteration features that typify a completely mature gossan. For example, although only traces of relict sulphides occur in the uppermost, near-surface zone, the almost invariable presence of these sulphides, especially chalcopyrite, is an indication of the incompleteness of the oxidizing and leaching processes. The lack of maturity also is manifested not only by the shallowness of the interval over which appreciable sulphide oxidation has occurred, but also by the preservation of abundant magnetite grains throughout the oxidized portion of the tailings.

Alteration intensity of the Waite Amulet tailings has been classified on a scale of 0 to 10. The purpose of the introductory remarks above is to emphasize that a rating of 10 does not signify that oxidation is virtually complete; the value is only a relative measure, and in the present scheme a 10 rating indicates that pyrrhotite and pyrite have been obliterated and only traces of sulphide, typically chalcopyrite, remain. A rating of 9 indicates that a few grains of pyrite are observable in an otherwise sulphide-purged oxidized sample. The appearance of vestiges of pyrrhotite would lower the alteration rating to an 8 or 7, the value depending on the number of remnants observed and their degree of preservation. Values below 7 are in essence measures of the intensity of pyrrhotite alteration; this alteration is reflected both by textures (e.g., residual sulphide cores versus only narrow alteration rims), and by the proportions of pyrrhotite grains affected to one degree or another.

The following comments briefly summarize the features observed in polished sections. Additional data are given in Table 4, and Figures 8 and 9 consist of cross-sections illustrating the variations in alteration intensity with depth in each borehole.

Hole WA-2

Six polished sections of core from borehole WA-2 were examined microscopically. The upper part of the hole is strongly oxidized, and the change to relatively unaltered material is sharply demarcated in core sample C-2. Indications of a weakly copper-enriched supergene zone are present in sample C-5.

Hole WA-8

Nine polished sections were examined. A peculiar feature is that all deeper samples consist of material that falls in the very fine-grained category (Table 4). Weak alteration extends to greater depths than that in WA-2, but otherwise the alteration profiles of the two holes are similar (Fig. 8). The magnetite content in WA-8 is noticeably lower than that of other holes.

Hole WA-11

Twenty polished sections were examined. As in the preceding holes (WA-2, WA-8) the uppermost samples are strongly oxidized and the downward progression is to negligible alteration. In WA-11, however, a second strongly oxidized zone appears at sample C-6 (Fig. 8). This thin zone is interpreted to be an oxidized paleosurface, probably continuous with similar zones noted in holes WA-1 and WA-17 (Table 3).

Hole WA-22

The eleven polished sections examined show the normal trend of decreasing alteration intensity with increasing depth, but the change is more gradual than in other holes (Fig. 8). The uppermost, strongly oxidized zone is typically almost devoid of sulphides, and traces of covellite appear at the bottom of this zone (sample C-3B). Marcasite was observed in three of the polished sections in the weakly altered zone, and this mineral also was noted to occur in the weakly to negligibly altered parts of holes WA-8 and WA-11.

Hole WA-17

Nearly all of the 15 polished sections examined consist of coarse-grained material (Table 4). The strongly oxidized zone near surface is rather shallow (Fig. 9) and the underlying samples (C-2,3,4) contain traces of covellite. Samples C-6 and C-7 include material from moderately oxidized paleosurfaces. The alteration intensity of samples in the moderately oxidized zone is difficult to rate numerically because most samples contain a relatively high proportion of unaltered pyrrhotite.

Hole WA-1

As in WA-17, nearly all of the 18 samples examined from hole WA-1 consist of coarse-grained material. The strongly oxidized zone is relatively thick and is fairly well demarcated, and a zone of paleosurface oxidation is present at sample positions C-8 and C-9 (Fig. 9).

Hole WA-20

Polished sections from the 10 sample sites in hole WA-20 (Jambor 1986) were re-examined in order to obtain comparable ratings for the alteration intensity. All of the samples fall within the coarse-grained textural

category. The interruption in the trend of colour change previously noted at sample C-6 (Table 2 in Jambor 1986) may reflect the presence of a paleosurface at this position. The overall alteration profile for hole WA-20 is similar to that of WA-17 (Fig. 9).

Summary

The megascopic and microscopic observations have revealed a few patterns that were not evident in previous studies. The downward progression from an oxidized, sulphide-depleted zone near surface to an unaltered zone at depth is obvious, but additional much more subtle variations are present. Firstly, the cores from the northern end of the tailings pile (WA-2 and WA-8 in Fig. 2) are consistently much finer grained than those from the remainder of the pile. The boundary between the finer and coarser grained areas lies between hole WA-8 and the east-west cross-section (WA-17 to WA-20 in Fig. 2). Secondly, the east-west boundary also seems to mark the limit and approximate strike of a conspicuously oxidized paleosurface that is readily identified in at least 3 of the 4 holes in the section (Fig. 9). Thirdly, the two holes which yielded the finer grained material (WA-2 and WA-8) not only have the thinnest zones of strong oxidation, but they also lack a zone of moderate alteration (compare, for example, the profiles for holes WA-2 and WA-8 versus WA-22, WA-17, WA-1, and WA-20). The difference may be related to grain size, with less oxidant penetration occurring in the finer grained material, but a more likely control is restricted oxidation because of the higher water table at WA-2 and WA-8 (Fig. 3). The difference, however, also could be related to minor oxidation that occurred during the accumulation of the tailings pile. The inference is that holes WA-2 and WA-8 are sited in an area where the most recent deposition of tailings occurred, but the validity of this inferred chronological (stratigraphic) sequence is not known to the writer. Fourthly,

covellite had not been detected previously but was observed in 11 of the samples from the current suite. Only 1 of the occurrences is in the near-surface strongly oxidized zone, but 9 of the 11 are in the underlying zones of moderate alteration. Lastly, the distribution of marcasite is similar to that noted in hole WA-20 (Jambor 1986). Thus the oxidation profiles again can be broadly generalized into (a) a sulphide-depleted, strongly oxidized near-surface zone; (b) an intermediate zone in which only moderate to weak alteration has occurred, and marcasite has formed by replacement of pyrrhotite; (c) an unaltered zone at depth where the tailings are in a relatively pristine state.

CHEMICAL ANALYSES

The previous studies of Waite Amulet cores showed that combined megascopic and microscopic studies provide a reliable measure of the state of alteration of the tailings, and that specific chemical analyses can be used to quantify the abundances of some of the various alteration minerals (Jambor 1987). Because of the large number of samples available for the present study, and the impracticality of chemically analyzing all of them, the megascopic-microscopic observations were used as a guide to reduce the number of samples for analysis. Nearly all of the samples selected for deletion were from the water-saturated zone. Because some of the individual cores had been split into sub-samples, however, and because of the desire to maintain not-too-distant intervals even in the water-saturated zone, the result was that 50 samples were analyzed. As in the previous studies the interpretations, supported by the mineralogical studies, are that the water-soluble fraction of the tailings contains the $FeSO_4.nH_2O$ and $CaSO_4.nH_2O$ minerals,

that the analyses for elemental sulphur reflect the presence of native sulphur, and that the sulphate fraction which is not water-soluble is bound in jarosite.

Table 5 lists the results of the chemical analyses, and also the calculated amounts of SO_4 required to use up all of the Ca and Fe in the water-soluble fraction. Additional SO_4 not required by the Ca and Fe compounds is tabulated as Remnant SO_4. The final column in Table 5 gives the value obtained by subtraction of the wt. % water-soluble sulphate from that of total sulphate; the value is in essence a measure of the amount of jarosite present in each sample because jarosite is the only less-soluble sulphate mineral known to occur in the tailings, and its presence in relatively copious amounts is readily verifiable.

pH results

The pH values in Table 5 represent determinations done on the unfiltered sample-water suspensions used for the analyses of the water-soluble constituents. The pH values range from 8.0 to 3.3, but systematic trends are evident. The two highest pH values (8.0 and 6.3 in samples WA-8, C-2 and C-3) are from near-surface material to which there presumably has been addition of agricultural limestone: both core samples are carbonate-rich and have been confirmed by X-ray diffraction to contain calcite. Except for these 2 samples, the pH range is 5.8 to 3.3; the trend from low pH values in the upper oxidized zone to higher values in the unaltered tailings at depth is well defined (Fig. 10, 11).

Water-soluble constituents

The Fe contents of the water-soluble fraction average less than 0.03 wt. %. The highest value, 0.23 wt. %, is from sample WA-11, C-3, which has been

confirmed to contain siderotil, $FeSO_4.5H_2O$. The cross-section profiles (Fig. 12, 13) show clear indications that water-soluble iron is depleted in the strongly oxidized zone and accumulates or is generated in the underlying zone of moderate oxidation.

$CaSO_4$ variations are shown in Figures 14 and 15. The highest values generally occur in the strongly oxidized zone and in the upper, adjoining part of the moderately oxidized zone. The uppermost samples in holes WA-8, WA-11 and WA-2 (Fig. 15) are low in gypsum and are at the vegetation-rich surface of the tailings.

Remnant SO_4

Soluble sulphate not attributable to $CaSO_4$ or $FeSO_4$ is generally low, but exceeds 0.3 wt. % in 10 samples (Table 5). The anomalously high values have two distinct distributions, with roughly half of the high values occurring at the break between the strongly and moderately oxidized zones (i.e., roughly at the depth of the C-3 sample positions). The remaining half of the high values is from samples in hole WA-8, but these samples are not altered significantly. Previous attempts to identify a cation that is bound with the remnant SO_4 were unsuccessful (Jambor 1987), and no appropriate water-soluble sulphate has been observed in the present study. In strongly oxidized material, however, sulphate-bearing ferrihydrite is present (Table 6). All of the ferrihydrite is poorly crystalline and gel-like, and presumably part of the absorbed sulphate is water-soluble. In the reverse process, expulsion of absorbed water is evident from the "mud crack" structure (Fig. 21) that develops as a result of desiccation during room-temperature drying.

Elemental sulphur

The distribution profiles for elemental sulphur are shown in Figures 16 and 17. The highest sulphur values generally occur toward the base of the strongly oxidized zone. Excluding previously studied hole WA-20, and the three highest values in the present study, the remaining 47 samples average 0.16 wt. % S. Of the aforementioned three highest values, two are from jarosite-rich samples; the other sample, however, is not especially rich in jarosite but the presence of native sulphur could not be confirmed.

Insoluble sulphate

The last column in Table 5 represents the sulphate that is not readily soluble in water, and in essence the values are a measure of jarosite content. The correlation between observed jarosite occurrences and the chemical data is excellent, and the oxidation profiles (Fig. 18, 19) show that alteration intensity and insoluble sulphate have remarkably similar trends.

MINERALOGICAL OBSERVATIONS

The initial mineralogical study of the Waite Amulet tailings (Jambor 1986) focused specifically on the identification of the minerals that make up the fine-grained, complex alteration products. The subsequent studies (Jambor 1987, and this work) have had a broader, less focused chemical-mineralogical approach. Nevertheless, the more recent studies have considerably expanded the mineralogical data base and have shown that some false impressions were obtained from the examination of core WA-20. For example, the water-soluble sulphate fraction from WA-20 was thought to have been derived largely from bassanite, $2CaSO_4.H_2O$, and it was thought that the calcium contribution might have been derived, or at least enhanced, by the

addition of lime to the tailings surface. The newer studies have shown that virtually all of the soluble calcium is present as gypsum, $CaSO_4.2H_2O$, that occurs as euhedral single crystals up to 1 mm long. These crystals are distinguished readily from the small amount of fine-grained gypsum that crystallizes from the solutions evaporated during drying of the as-received cores. The relative coarseness of the crystals, their uniform size, and their occurrence throughout the tailings (including the water-saturated zone) suggest that gypsum formation, rather than being related specifically to lime addition, is more likely a natural and integral part of the chemistry of the whole tailings system.

The present study also has given indications of what happens to the small amounts of copper and zinc in the tailings. Chalcopyrite is surprisingly resistant to dissolution in the oxidation zone; eventually however, the mineral is leached and part of the copper is precipitated as covellite, thus emulating supergene alteration. The remainder of the copper, plus that eventually contributed by the breakdown of covellite, is incorporated in trace amounts as a solid-solution element in sulphates. Most of the copper occurs in the water-soluble sulphates and thus is eventually flushed out of the system. Unlike copper, zinc from the breakdown of sphalerite remains in solution or is ephemerally precipitated only in the $(Fe,Zn,Cu)SO_4.nH_2O$ sulphates.

Iron derived from the oxidation of pyrite, pyrrhotite, and magnetite to a lesser extent, is precipitated locally in small amounts as the soluble iron sulphates $FeSO_4.nH_2O$. On dried cores the prevalent species is ferrohexahydrite ($FeSO_4.6H_2O$), but coexisting siderotil ($FeSO_4.5H_2O$) also has

been identified. On one sample minute amounts of an unidentified Ca-Fe sulphate occur as a bloom associated with ferrohexahydrite and gypsum (Fig. 22). It is probable that the monohydrate (szmolnokite), the tetrahydrate (rozenite) and the heptahydrate (melanterite) exist at the tailings site; the highest of these hydrates precipitates readily in a moist environment, and dehydration to the tetrahydrate occurs rapidly under natural conditions once the moisture source is removed.

The ferrous sulphates are quantitatively insignificant precipitates when compared with the amount of iron that has been deposited as jarosite and various iron hydroxides. Although the sulphides in the near-surface zone have been oxidized, that much of the iron has remained in situ is evident from the widespread occurrence of oxides pseudomorphous after sulphides. The destruction of sulphides, which have high densities, coupled with the retention of iron in the oxidized zone, indicates that this zone should show a net increase in Fe wt. %. To achieve the formation of hardpan, it would be necessary to have additional leaching to remove the near-surface iron so that it could be redeposited and concentrated as an interstitial binding agent.

The jarosite in the Waite Amulet tailings is normal potassium jarosite. Presumably the potassium is derived largely from the destruction of K-feldspar, but alteration of silicates has not been examined. The highest jarosite content is in sample WA-11, C-3ox (Table 5); the jarosite-rich layered material in this sample could be considered as a primitive stage in the development of hardpan.

In the previous studies the presence of both goethite and lepidocrocite (two forms of FeOOH) was confirmed by X-ray diffraction patterns. In the present study these minerals have been noted to co-exist on an intimate scale, i.e., as mixtures that have replaced individual grains of pyrrhotite. Additionally, the common presence of ferrihydrite, ideally $5Fe_2O_3.9H_2O$, has been recognized in the strongly oxidized zone (Fig. 21, Table 6). Ferrihydrite typically is disordered and gives poor X-ray diffraction patterns, but observations suggest that this mineral is widespread in small amounts. In the saturated zone, for example, what is either ferrihydrite or amorphous iron oxide-hydroxide appears as a glazed brownish coating on grain aggregates, but the glaze is too thin, or the crystallinity too poor, to obtain confirmation by X-ray diffraction. In the strongly oxidized zone, however, a few of the coatings are considerably thicker, and local concentration into sedimentary-type layers up to 1 mm thick have been observed.

Ferrihydrite is unstable with respect to goethite and hematite, and the transformation occurs in a variety of conditions (Torrent and Guzman 1982; Torrent et al. 1982). Lepidocrocite is metastable with respect to goethite, and it has been concluded that the formation of lepidocrocite involves the presence of Fe^{2+} as a necessary precursor (Schwertmann 1985). Silica evidently inhibits crystallization of goethite and lepidocrocite, thereby favouring the formation of ferrihydrite (Carlson and Schwertmann 1981 ; Cornell et al. 1987). Thus, it may be significant that the analyses of Waite Amulet ferrihydrite indicate the presence of small amounts of Si (Table 6), but the silica contents nevertheless are minor as compared to sulphate.

Recommendation for further studies

Two additional aspects of the Waite Amulet mineralogy merit additional study. Firstly, the alteration of silicate minerals has not been investigated and at this point it is only an assumption that the breakdown of K-feldspar in the strongly oxidized zone is the principal source of the potassium that is precipitated from solution as jarosite. Likewise, if gypsum precipitates have not derived their calcium from the surficial agricultural lime, then other silicate-consuming reactions must have occurred and should be identified. Secondly, a suite of oxidized samples and precipitates was collected by this writer at the Waite Amulet tailings site in July 1987. Mineralogical characterization of these specimens should be done; possibly the precipitates being formed by seepage from the tailings differ from those formed within the tailings pile.

Whole-rock chemical analyses of some of the tailings cores might prove to be useful in charting the mineralogical reactions that are manifested in the oxidation profiles. Chemical analyses for total sulphur would be a simple method of quantitatively demonstrating the extent of sulphide destruction in the strongly oxidized material; sulphide-sulphur values should correlate with the microscopically determined alteration intensity (Fig. 8,9). Finally, to obtain an estimate of the quantity of sulphides that are in the tailings pile, the previously studied samples from the piezometric sites are being examined by image analysis to obtain their pyrite and pyrrhotite contents; these values will give an indication of the amount of sulphides that are a potential source of acid drainage.

CONCLUSIONS

Microscopic studies and chemical analyses of the Waite Amulet tailings have shown consistent trends of alteration wherein a strongly oxidized, sulphide-depleted near-surface zone gives way to pristine unaltered tailings at depth. In most holes the strongly oxidized zone is underlain by a variable thickness of weak alteration (the intermediate zone); the intensity of alteration in the intermediate zone appears to be greatest along the edge of the tailings (e.g., in hole WA-20). In addition to these general trends, a thin zone of moderate alteration trends approximately east-west across the tailings pile at intermediate depths and marks a zone of paleosurface oxidation.

In the strongly oxidized zone nearly all of the pyrrhotite and pyrite have been destroyed. The principal alteration products are oxyhydroxides (goethite, lepidocrocite and ferrihydrite) and sulphates (jarosite and gypsum). Chemical analyses indicate that jarosite abundance correlates well with the microscopically observed alteration intensity. For the water-soluble fraction of the tailings, pH values generally range from 5.8 to 3.3; the trend from low values in the upper oxidized zone to higher values in the unaltered tailings at depth is readily apparent. Water-soluble Fe is highest in the moderately oxidized zone, whereas the highest values for $CaSO_4$ generally occur in the strongly oxidized and adjacent moderately oxidized zones. Sulphate in the tailings has been derived from the oxidation of sulphides, and presumably the breakdown of K-feldspar has provided the potassium incorporated in the jarosite precipitates. Partial destruction of other silicates may have provided the calcium now present as extensive gypsum precipitates, but this aspect of alteration needs further study.

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REFERENCES

Carlson, L. and Schwertmann, U. (1981): Natural ferrihydrites in surface deposits from Finland and their association with silica. Geochim. Cosmochim. Acta 45, 421-429.

Cornell, R.M., Giovanoli, R. and Schindler, P.W. (1987): Effect of silicate species on the transformation of ferrihydrite into goethite and hematite in alkaline media. Clays Clay Minerals 35, 21-28.

Jambor, J.L. (1986): Detailed mineralogical examination of alteration products in core WA-20 from Waite Amulet tailings. Division Report MSL 86-137(IR); CANMET, Energy, Mines & Resources Canada.

Jambor, J.L. (1987): Mineralogical and chemical investigation of cores from piezometric sites in Waite Amulet tailings, Noranda, Quebec. Division Report MSL 87-32(IR); CANMET, Energy, Mines & Resources Canada.

Petruk, W. and Pinard, R.G. (1986): Mineralogical and image analysis study of samples from core WA-20 of the Waite Amulet tailings. Division Report MSL 86-87(IR); CANMET, Energy, Mines & Resources Canada.

Schwertmann, U. (1985): The effect of pedogenic environments on iron oxide minerals. In Advances in Soil Science, vol. 1, ed. B.A. Stewart. Springer-Verlag, New York; 171-200.

Siwik, R.S. (1986): Hydrogeochemical investigation of reactive tailings at the Waite Amulet tailings site, Noranda, Quebec - 1985 program. Contract Report OSQ85-00101.

Torrent, J. and Guzman, R. (1982): Crystallization of Fe (III)-oxides from ferrihydrite in salt solutions: osmotic and specific ion effects. Clay Minerals 17, 463-469.

Torrent, J., Guzman, R. and Parra, M. (1982): Influence of relative humidity on the crystallization of Fe(III) oxides from ferrihydrite. Clays Clay Minerals 30, 337-340.

Table 1. Core samples which showed an acid attack on container boxes after the drying process

Borehole and Sample Numbers		Character of Core Sample	Strength of Stain
WA-2,	C-1:	upper half oxidized, lower half sulphide-rich	light browning
WA-8,	C-4:	yellowish brown, strongly oxidized except for bottom 1cm	light browning
	C-5:	sulphide-rich, black	moderate browning
	C-6:	sulphide-rich, black	strong browning
	C-7:	sulphide-rich, black	very strong
	C-8:	sulphide-rich, black	dark brown*
	C-9:	sulphide-rich, black	strong browning
	C-10:	sulphide-rich, black	light browning
WA-11,	C-9:	sulphide-rich, black	strong browning
	C-11:	sulphide-rich, black	strong browning
	C-13:	sulphide-rich, black	strong browning
	C-15:	sulphide-rich, black	moderate browning
WA-22:		no staining observed	
WA-1,	C-13 to C-18 inclusive	all are black, sulphide-rich	all showed strong browning
WA-17,	C-5:	sulphide-rich, black	light browning
	C-7:	top 2 cm moderately oxidized, remainder black	strong browning
	C-9:	sulphide-rich, black	light browning
	C-12:	sulphide-rich, black	light browning
	C-13:	sulphide-rich, black	light browning
WA-20:		samples received after drying - - no data	

*darkest brown, most intense reaction of all samples

Table 2. Water-soluble sulphate in samples which showed acidity losses (Table 1) versus results from new samples.

Borehole Sample Nos.	Strength of Stain*	Chem. Anal., Wt.%				Calc. Distributions, Wt.%		
		ph	Fe	Ca	SO_4	SO_4 as $CaSO_4$	SO_4 as $FeSO_4$	Remnant SO_4
WA-8, C-8	dark brown	4.8	0.13	0.46	1.98	1.10	0.22	0.66
C-8Q	-	4.6	0.06	0.45	1.35	1.08	0.10	0.17
WA-8, C-9	strong browning	4.3	0.07	0.39	1.17	0.94	0.12	0.11
C-9Q	-	4.4	0.05	0.46	1.38	1.10	0.09	0.19
WA-8, C-10	light browning	5.7	<0.01	0.42	1.26	1.01	0.00	0.26
C-10Q	-	6.1	<0.01	0.46	1.44	1.15	0.00	0.29

*see Table 1
Q = new sample, quartered core

Table 3. General megascopic features of the Waite Amulet core samples

Borehole	Sample Number	Megascopic Features	Special Items	Category
WA-2	-	5 core samples, each 21 cm to 23 cm long		
	C-1	surface sample with scattered vegetation at top, clay-rich for first 5 cm; remainder yellow-orange, ocherous, strongly oxidized and without sulphides		surface sample, strongly oxidized
	C-2	upper quarter stongly oxidized, ocherous, followed by clay-like* second quarter; remainder black, sulphide-bearing	sub-sampled as C-2 top and C-2 bottom (clay-like zone omitted)	contact between leached (sulphide-depleted) and sulphide-rich zones
	C-3	black, sulphide-rich		sulphide zone
	C-4	black, sulphide-rich		sulphide zone
	C-5	black, sulphide-rich		sulphide zone
WA-8	-	10 samples; 16 cm to 18 cm long except for C-5 (13 cm)		
	C-1	surface sample of clay with minor vegetation	carbonate-rich	surface clay
	C-2	surface clay, as above	carbonate-rich	surface clay
	C-3	clay in uppermost third of core, gradational to strongly oxidized, ocherous remainder	clay-rich fraction at top is carbonate-rich and was deleted from chem. sample	clay gradational to strongly oxidized
	C-4	strongly oxidized, ocherous except that last cm is dark grey, sulphide-bearing		strongly oxidized
	C-5 to C-10 incl.	black, sulphide-rich; rind of ocherous material removed from C-5 and C-6		sulphide zone
WA-11	-	15 samples, from 19 cm to 22 cm long		
	C-1	ocherous, strongly oxidized with abundant vegetation at top	sub-sampled as C-1 top and C-1 bottom	strongly oxidized

Table 3. General megascopic features of the Waite Amulet core samples (cont'd.../2)

Borehole	Sample Number	Megascopic Features	Special Items	Category
	C-2	ocherous, strongly oxidized		strongly oxidized
	C-3	upper half oxidized, lower half sulphide-rich; the two are separated by a 1-1.5 cm highly ocherous zone	sub-sampled: top; intermediate strongly ocherous zone; bottom sulphide-rich zone	contact between sulphide-depleted and sulphide-rich zones
	C-4	black, sulphide-rich		sulphide zone
	C-5	black, sulphide-rich, with uppermost quarter very fine-grained	sub-sampled as uppermost quarter, and remainder	sulphide zone
	C-6	grey to black with diffuse, weak oxidation in upper half, gradational downward to strongly oxidized 3-4 cm zone at bottom	sub-sampled as top half, bottom half	local oxidation, paleosurface
	C-7	about 0.5 cm oxidation at top; remainder black, sulphide-rich		mainly sulphide zone
	C-8 to C-15 incl.	black, sulphide-rich		sulphide zone
WA-22	-	sample C-1 15 cm long; all others 17 to 21 cm long		
	C-1	surface sample with abundant vegetation at top; strongly oxidized, but less ocherous than WA-11		strongly oxidized
	C-2	strongly oxidized, better layering than in C-1		strongly oxidized
	C-3	upper half similar to C-2, followed by a 2-3 cm zone of more strongly ocherous material which is gradational downward to black, sulphide-rich material	sub-sampled as top zone, middle ocherous zone, and bottom	transitional from oxidized to sulphide-rich
	C-4	weakly oxidized layers in upper third; remainder black, sulphide-rich		weakly oxidized, mainly sulphide-rich
	C-5 to C-9 incl.	black, sulphide-rich		sulphide zone

Table 3. General megascopic features of the Waite Amulet core samples (cont'd.../3)

Borehole	Sample Number	Megascopic Features	Special Items	Category
WA-17	-	15 samples from 16 cm to 21 cm long		
	C-1	surface sample with 0.5 cm of soil at top and abundant vegetation; remainder strongly oxidized, yellowish brown	0.5 cm soil removed	strongly oxidized
	C-2	strongly oxidized, excellent varve-like layering gradational downward to sandier, thicker layers		strongly oxidized
	C-3	grey to black, sulphide-rich but with local weak oxidation		mainly sulphide-rich
	C-4	black, fine-grained, well-layered		sulphide zone
	C-5	black, well-layered		sulphide zone
	C-6	black, sulphide-rich for 3-3.5 cm, succeeded by a 3-4 cm zone of moderate oxidation along a vegetation-bearing paleosurface, and then 5 cm of black, sulphide-rich; remainder gradational to moderately strongly oxidized, partly ocherous, vegetation-bearing paleosurface		mixed sulphide and oxidized zones at paleosurfaces
	C-7	a 0.5 cm thick, vegetation-bearing, irregular, strongly oxidized yellowish zone near the core top; remainder black, sulphide-rich		mainly sulphide zone
	C-8	black, sulphide-rich; a large vug 2.5 cm long and 5 cm wide is almost the full diameter of the core, but not visibly oxidized		sulphide zone
	C-9	black, sulphide-rich		sulphide zone
	C-10	black, sulphide-rich; a weakly oxidized(?) greenish yellow interior zone		sulphide zone
	C-11 to C-15 incl.	black, layered, normal sulphide-rich		sulphide zone

Table 3. General megascopic features of the Waite Amulet core samples (cont'd.../4)

Borehole	Sample Number	Megascopic Features	Special Items	Category
WA-1	-	18 cores, with C-1 to C-9 15 to 18 cm long, and C-10 to C-17 18 cm to 21 long; core C-18 was 26 cm long		
	C-1	surface sample; clay-like with abundant organic material	carbonate-rich	surface clay
	C-2	strongly oxidized, orange-brown ocherous		strongly oxidized
	C-3, C-4	similar to C-2		strongly oxidized
	C-5	less brownish, more yellowish; last 2-3 cm is black		strongly oxidized
	C-6, C-7	black, sulphide-rich, variable from very fine-grained to relatively coarse layers		sulphide zone
	C-8	upper 5-6 cm is strongly oxidized and includes a small amount of organic material; remainder black, friable	sub-sampled into top and bottom zones	oxidized paleo-surface and underlying sulphide zone
	C-9	black, friable upper half similar to that in C-8 but with minor oxidized zone at top; bottom half consists of oxidized interior surrounded by a black shell (proportions of core and shell about 1:1) -- structure suggests that the interior, oxidized material is more representative of the sample site		mixture of oxidized and sulphide-rich zones
	C-10	upper 4 cm strongly oxidized; remainder black, sulphide-rich		mainly sulphide zone
	C-11 to C-18 incl.	black, sulphide-rich		sulphide zone
WA-20	-	upper, strongly oxidized zone progresses downward to unaltered, sulphide-rich zone; see Jambor (1986)		

*Clay-like refers to particle size rather than to composition. Clay-like fractions are composed predominantly of fine-grained tailings silicates.

Table 4. Microscopic characterization of Waite Amulet samples

Drillhole, Sample No.	Relative Grain Size*	Alteration Features	Alteration Intensity
WA-2, C-1	coarse magnetite	strongly oxidized, traces of pyrite (py) and chalcopyrite (cp) are sole sulphides; Fe hydroxide rims numerous	9.5
C-2T*	-	trace sulfides only; Fe hydroxide rims abundant	9.5
C-2B	very fine-grained	mixture of strongly oxidized as above, plus only weakly altered sulphides -- transition zone	1
C-3	very fine-grained	abundant pyrrhotite (po) -pyrite (py); most po intact, but many grains have weakly altered rims	1
C-4	very fine-grained	similar to C-3 but much less altered	0
C-5	coarse with numerous f.g. clumps	negligible alteration of po, but several grains of covellite observed, indicating a probable zone of supergene enrichment	0
WA-8, C-3	coarse	strongly oxidized; trace sulphides (mainly cp); Fe hydroxide rims abundant; traces of covellite	10
C-4	intermediate	texture consists of coarse grains mixed with clumps of very fine-grained material; mainly strongly oxidized as in C-3; some clumps contain py-cp-po, suggesting abrupt contact with unoxidized material	10
C-5	very fine-grained	most po grains fairly fresh, but fine grain size hinders observations; some po grains have thin alteration rims	1-2
C-6	very fine-grained	weak alteration at a few po grain edges	0-0.5
C-7	very fine-grained	similar to C-6	0-0.5
C-8	very fine-grained	similar, but a few grains also show alteration to probable marcasite	0.5
C-9	very fine-grained	scattered coarse grains; only traces of rim alteration	0
C-10	very fine-grained	similar to C-9	0

Table 4. Microscopic characterization of Waite Amulet samples (cont'd.../2)

Drillhole, Sample No.	Relative Grain Size*	Alteration Features	Alteration Intensity
WA-11, C-1T	coarse	low magnetite, trace cp; strongly oxidized	9.5-10
C-1	coarse	similar to C-1T, but Fe hydroxide rims and pseudomorphs more abundant	9.5-10
C-2	coarse	about 1% magnetite, 0.1% cp, both unaltered; strongly oxidized but without Fe hydroxide rims	9
C-3T	coarse	similar to C-2	9
C-3	coarse	less magnetite, but cp still common	9
C-3B	intermediate	scattered coarse grains plus clumps with very fine-grained sulphides; first appearance of py+po with po extensively altered and pseudomorphs common; several grains covellite	6
C-4	intermediate	texture as in C-3B; a few po pseudomorphs but most alteration limited to po rims	4
C-5T	intermediate	upper quarter of core; negligible alteration	0
C-5	coarse	negligible alteration	0
C-6T	intermed.-coarse	mainly coarse grains with numerous clumps containing moderate amounts of very fine-grained sulphides; po variable from fresh to grains with only remnant cores -- suggests a blend of altered and unaltered zones (low alteration rating reflects the higher proportion of fresh grains)	2
C-6B	coarse	predom. strongly oxidized, low sulphide; trace covellite	8
C-7	coarse	negligible alteration	0
C-9	intermediate	negligible alteration	0
C-10	coarse	negligible alteration; scattered strongly altered aggregates, presumably contamination	0

Table 4. Microscopic characterization of Waite Amulet samples (cont'd.../3)

Drillhole, Sample No.	Relative Grain Size*	Alteration Features	Alteration Intensity
C-11	coarse	similar to C-10	0
C-12	intermediate	similar to C-10	0?
C-13	intermediate	similar to C-10; marcasite observed in rare altered grains	0
C-14	intermed.-coarse	similar to C-10	0-0.5
C-15	coarse	altered po rare, mainly to partial rims of marcasite	0-0.5
WA-22, C-1	coarse	well-developed Fe hydroxide rims on silicates and magnetite; several grains cp and a few py, po (a few grains po relatively unaltered-contamination?)	9
C-2	coarse	scattered cp, a few grains py, no po; Fe hydroxide rims less abundant than in C-1	8.5
C-3	coarse	upper part of core; only cp seen	8.5
C-3M	intermediate	mainly fine- to medium-grained clumps with scattered coarse magnetite; py preserved in many of the clumps, Fe hydrox.-jarosite cementation of clumps clearly visible	7
C-3B	coarse	po alteration mainly along parting rather than rims; several grains of covellite observed	3
C-4	coarse	much po weakly to moderately altered; marcasite present	4
C-5	coarse	similar to C-4 but po alteration less intense	3.5
C-6	coarse	po alteration mainly at rims, which include some marcasite	4
C-7	coarse	similar to C-6, including marcasite, but alteration less intense	2.5
C-8	coarse	only scattered grains weakly altered	0-0.5
C-9	coarse	similar to C-8	0-0.5

Table 4. Microscopic characterization of Waite Amulet samples (cont'd.../4)

Drillhole, Sample No.	Relative Grain Size*	Alteration Features	Alteration Intensity
WA-17, C-1	coarse	excellent Fe hydroxide rims on silicates and some magnetite grains; traces of cp, py	9-9.5
C-2	coarse	po present but most grains partly replaced	4
C-3	intermediate	mixed coarse grains with abundant clumps containing fine-grained sulphides; traces of covellite noted in C-2 and C-3; many po grains fresh	2.5
C-4	coarse	similar to C-3 but more po grains altered; traces of covellite present	3
C-5	coarse	similar to C-4	2.5-3
C-6	coarse	similar to C-5	3.5
C-7	coarse	some po grains strongly altered; a few Fe hydroxide rims present on silicates	4
C-8	coarse	numerous clumps with very fine-grained sulphides; alteration mainly at po rims	3.5
C-9	coarse	abundant clumps - texture nearly intermediate; po weakly rim-altered	1
C-10	intermediate	both coarse and fine-grained sulphides abundant; most po fresh, but a few grains moderately altered	0.5
C-11	coarse	clumps with fine- to medium-grained sulphides are abundant; weak rim alteration of some po	0.5
C-12	coarse	C-12 to C-15 inclusive: only traces of alteration, negligible overall	0
C-13	coarse		0
C-14	coarse		0
C-15	coarse		0

Table 4. Microscopic characterization of Waite Amulet samples (cont'd.../5)

Drillhole, Sample No.	Relative Grain Size*	Alteration Features	Alteration Intensity
WA-1, C-2	coarse	oxidized strongly but several grains cp, trace py noted; Fe hydroxide rims abundant, but thin	9.5
C-3	coarse	similar to C-2 but rims more pronounced	10
C-4	coarse	similar to C-3	10
C-5	coarse	similar to C-2	10
C-6	coarse	po abundant, altered variably from pseudomorphs to fresh but majority altered moderately	5
C-7	coarse	po variable from fresh to extensively altered -- high proportion of fresh grains	3.5
C-8T	coarse	po variable from fresh to pseudomorphed	3
C-8B	coarse	alteration variable as in C-8T	2-2.5
C-9	coarse	mixed assemblage, in part strongly oxidized, but many fresh grains	3
C-10	coarse	most po fresh, but Fe hydroxide rims noted on silicates	1
C-11	coarse	negligible alteration	0
C-12	coarse	negligible alteration	0
C-13	coarse	coarse with abundant fine-grained clumps; negligible alteration	0
C-14	coarse	texture as in C-13; negligible alteration	0
C-15	intermed.	negligible alteration	0
C-16	intermed.	fine-grained clumps with numerous dispersed coarse grains as in C-15; alteration negligible	0
C-17	intermed.	similar to C-16	0
C-18	intermed.	similar to C-16	0

*Suffixes: T=top, M=middle,, B=bottom, ox=oxide-rich

Table 5. Chemical analyses and calculated SO_4 distributions in Waite Amulet tailings

Drillhole, Sample No.	pH	Chem. Anal., Water-Soluble Fraction (wt.%)			Calculated Distributions (wt.%)			Chem. Anal., Whole Sample		Total SO_4 Minus Water-Soluble SO_4
		Fe	Ca	SO_4	SO_4 as $CaSO_4$	SO_4 as $FeSO_4$	Remnant SO_4	elemental S(wt%)	Total SO_4 (wt%)	
WA-2, C-1	4.2	<0.01	1.00	2.49	2.40	0.00	0.09	<0.01	4.67	2.18
C-2T*	3.8	0.01	0.90	2.46	2.16	0.02	0.30	0.06	4.22	1.76
C-3	4.0	0.15	0.84	3.00	2.01	0.26	0.99	0.12	3.15	0.15
C-4	4.1	0.15	0.71	2.58	1.70	0.26	0.88	0.01	3.09	0.51
C-5	4.2	0.02	0.69	1.92	1.66	0.03	0.26	0.08	2.13	0.21
WA-8, C-2	8.0	0.01	0.16	0.09	0.38	0.02	-	0.06	0.12	0.03
C-3	6.3	<0.01	1.40	3.42	3.36	0.00	0.06	0.19	5.48	2.06
C-4	4.1	<0.01	0.68	1.89	1.63	0.00	0.26	0.05	4.13	2.24
C-5	4.5	0.07	0.44	1.86	1.05	0.12	0.69	0.23	2.28	0.42
C-6	4.8	0.13	0.33	1.68	0.79	0.22	0.67	0.26	2.37	0.69
C-8	4.8	0.13	0.46	1.98	1.10	0.22	0.66	0.42	2.67	0.69
C-9	4.3	0.07	0.39	2.07	0.94	0.12	1.01			
C-10	5.7	<0.01	0.42	1.65	1.01	0.00	0.64			
WA-11,C-1T	3.8	<0.01	0.08	0.06	0.19	0.00	-	0.03	2.40	2.34
C-1	4.2	<0.01	0.22	0.54	0.53	0.00	0.01	0.01	3.33	2.79
C-2	3.8	<0.01	0.72	1.77	1.73	0.00	0.04	0.04	4.74	2.97
C-3T	3.6	<0.01	0.46	1.23	1.10	0.00	0.13	0.07	3.81	2.58
C-3ox	3.4	0.07	0.72	2.52	1.73	0.12	0.67	0.30	6.26	3.74
C-3	4.3	0.23	0.52	1.92	1.25	0.40	0.27	0.88	2.64	0.72
C-4	4.6	0.20	0.33	1.50	0.79	0.34	0.37	0.16	2.61	1.11
C-5	4.7	0.09	0.12	0.69	0.29	0.15	0.25	0.12	1.05	0.36
C-6T	4.5	0.14	0.38	1.44	0.91	0.24	0.29	0.16	2.79	1.35
C-6B	4.3	0.02	0.42	1.14	1.01	0.03	0.10	0.04	3.63	2.49
C-7	5.8	<0.01	0.19	0.60	0.46	0.00	0.14	0.13	0.72	0.12
C-11	5.1	0.01	0.71	1.98	1.70	0.02	0.26	0.05	1.98	0.00
C-15	4.8	<0.01	0.27	0.81	0.65	0.00	0.16	0.08	0.84	0.03
WA-22,C-1	3.8	<0.01	0.05	0.23	0.12	0.00	0.11	0.40	1.26	1.03
C-2	3.7	<0.01	0.32	0.87	0.77	0.00	0.10	0.33	2.13	1.26
C-3	3.5	0.01	0.52	1.35	1.25	0.02	0.08	0.61	3.06	1.71
C-3M	3.3	0.03	1.09	3.06	2.61	0.05	0.40	0.29	5.90	2.40
C-4	4.2	0.03	0.29	0.87	0.70	0.05	0.12	0.25	1.14	0.27
C-6	4.4	0.05	0.41	1.20	0.98	0.09	0.13	0.04	2.01	0.81
C-9	5.0	<0.01	0.33	0.93	0.79	0.00	0.14	0.14	0.99	0.06
WA-17,C-1	4.5	<0.01	0.74	1.77	1.77	0.00	0.00	0.09	4.10	2.33
C-2	4.1	0.01	0.85	2.16	2.04	0.02	0.10	0.25	3.63	1.47
C-3	4.5	0.03	0.38	1.20	0.91	0.05	0.24	0.19	1.74	0.54
C-4	4.2	0.02	0.28	0.99	0.67	0.03	0.29	0.15	1.95	0.96
C-6	4.3	0.01	0.44	1.26	1.05	0.02	0.19	0.19	2.07	0.81
C-9	4.5	0.03	0.55	1.53	1.32	0.05	0.16	0.17	1.65	0.12
C-14	5.0	<0.01	0.07	0.21	0.17	0.00	0.04	0.25	0.24	0.03

Table 5. Chemical analyses and calculated SO_4 distributions in Waite Amulet tailings (cont'd/2)

Drillhole, Sample No.	pH	Chem. Anal., Water-Soluble Fraction (wt.%)			Calculated Distributions (wt.%)			Chem. Anal., Whole Sample		Total SO_4 Minus Water-Soluble SO_4
		Fe	Ca	SO_4	SO_4 as $CaSO_4$	SO_4 as $FeSO_4$	Remnant SO_4	elemental S(wt%)	Total SO_4 (wt%)	
WA-1, C-2	4.5	<0.01	0.73	1.68	1.75	0.00	0.00	0.16	3.72	2.04
C-3	3.9	<0.01	0.67	1.62	1.60	0.00	0.01	0.26	3.92	2.30
C-4	3.4	<0.01	0.57	1.50	1.37	0.00	0.13	1.47	4.46	2.96
C-5	3.7	0.01	0.43	1.14	1.03	0.02	0.09	0.18	3.75	2.61
C-6	4.3	0.04	0.35	1.08	0.84	0.07	0.17	0.20	1.31	0.33
C-7	4.4	0.10	0.14	0.66	0.34	-	-	0.32	1.59	0.93
C-8T*	4.6	<0.01	0.60	1.44	1.44	0.00	0.00	0.28	3.06	1.62
C-8B*	4.3	0.11	0.13	0.66	0.31	0.19	0.16	0.33	1.86	1.20
C-9	4.2	0.04	0.39	1.20	0.93	0.07	0.20	0.32	2.70	1.50
C-10	4.6	0.02	0.31	1.02	0.74	0.03	0.25	0.09	1.89	0.87
C-11	5.3	<0.01	0.12	0.36	0.29	0.00	0.07	<0.01	0.45	0.09
C-16	4.4	0.03	0.52	1.53	1.25	0.05	0.23	<0.01	1.71	0.18

*Suffixes: T=top, M=middle, B=bottom, ox=oxide-rich

Table 6. Electron microprobe analyses of ferrihydrite in Waite Amulet tailings

		1	2
wt. %	Fe_2O_3	62.1	68.9
	Al_2O_3	0.9	0.4
	SiO_2	0.6	0.6
	SO_3	14.2	13.8
	Total	77.8	83.7
	(H_2O)	22.2	16.3

Sample WA-2, C-2T; grain mount

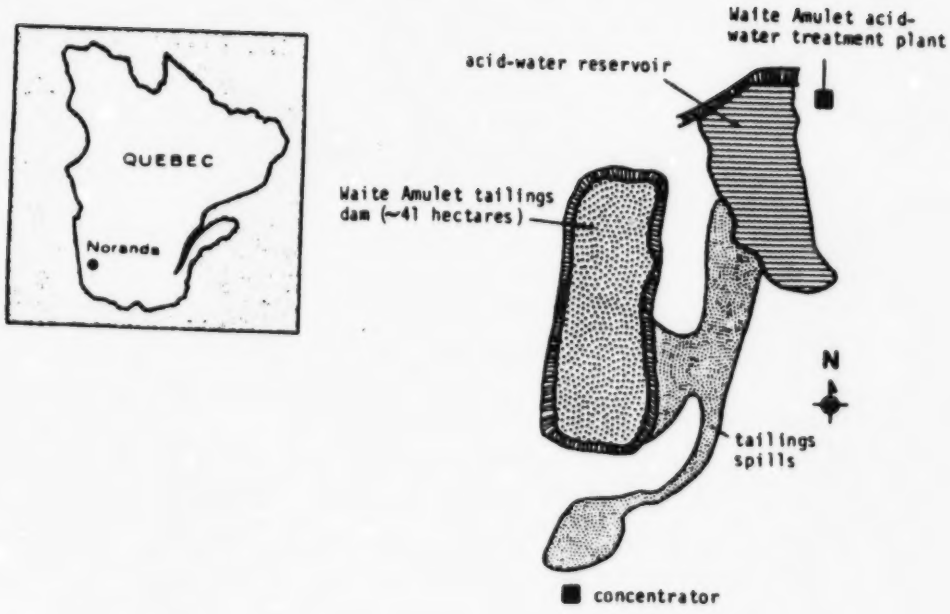

Fig. 1. General configuration of the Waite Amulet tailings dam and minesite.

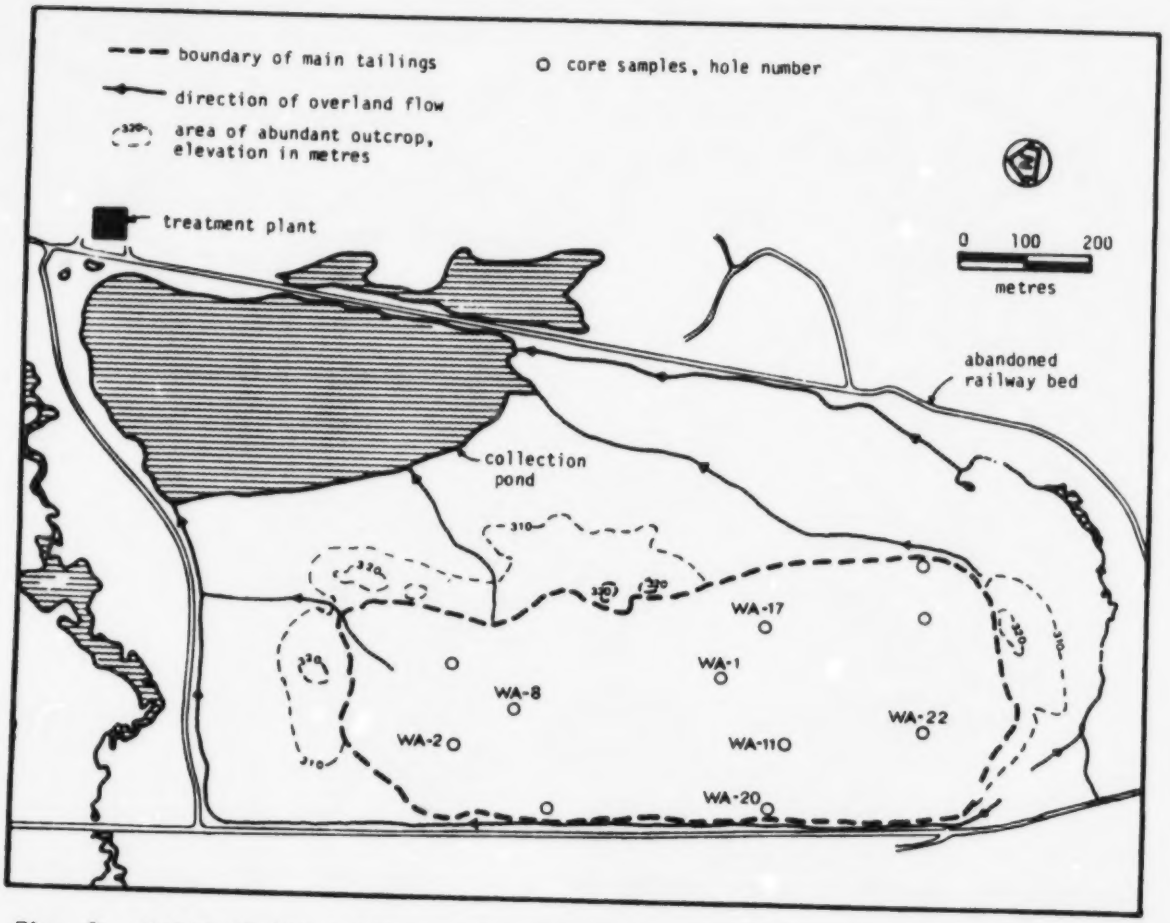

Fig. 2. Waite Amulet tailings pile and drainage pattern. Cored boreholes are shown by open circles; those with numbers were investigated in this study (except WA-20, which was described by Jambor 1986).

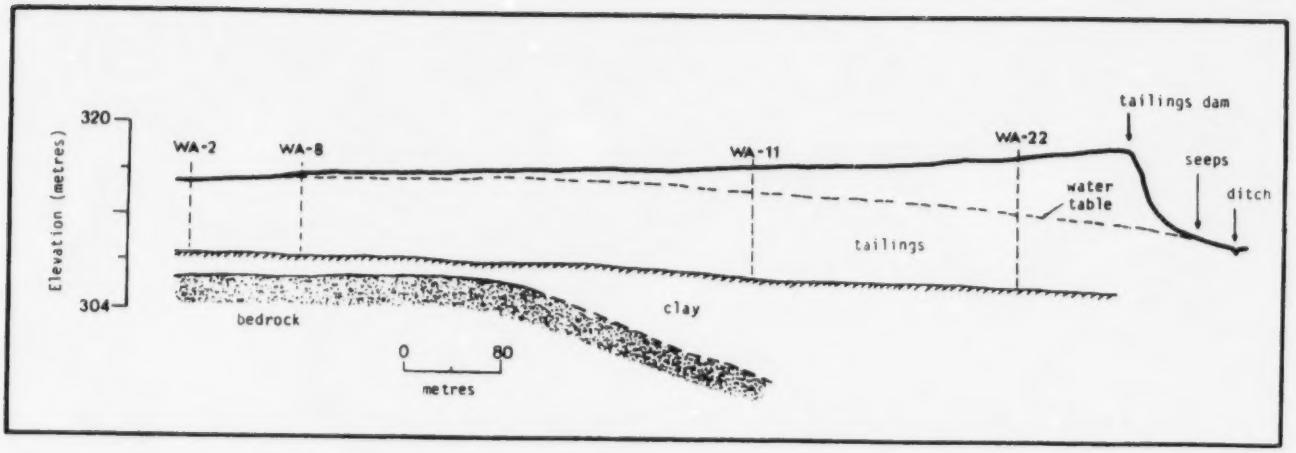

Fig. 3. Longitudinal section of the Waite Amulet tailings, showing the boreholes from which cores have been studied mineralogically. Borehole locations are shown in Figure 2.

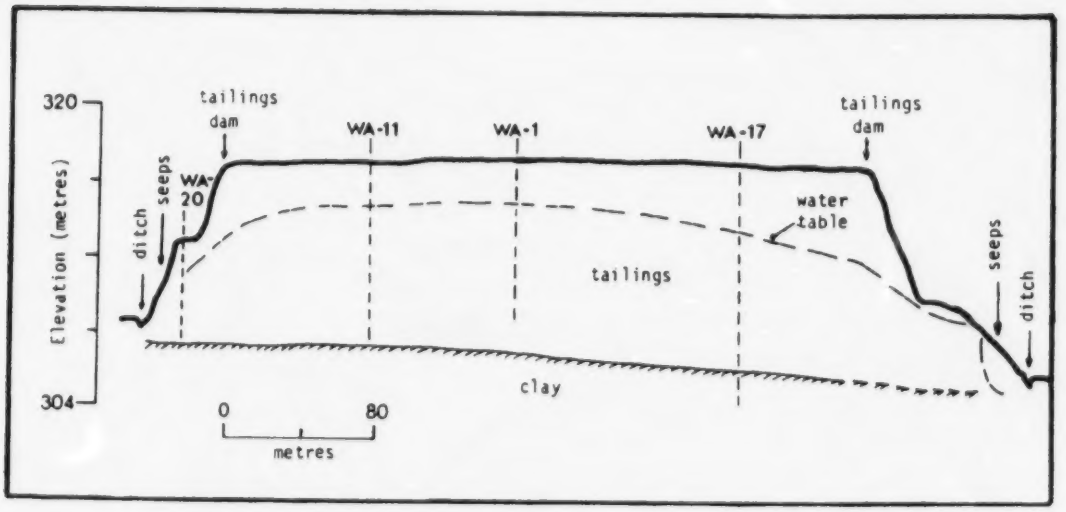

Fig. 4. Cross-section of the Waite Amulet tailings; section is approximately normal to the longitudinal section of Figure 3. Borehole locations are shown in Figure 2.

Fig. 5. Photographs of cores of Waite Amulet tailings. Tops face upward and bar scale at bottom right represents approximately 20 mm.

(a) WA-1, C-1, showing dark, vegetation-rich top underlain by lighter, massive clay-like fraction containing abundant calcite.

(b) WA-1, C-3, showing sand-sized tailings with bedding evident from darker, iron-stained layers.

(c) WA-17, C-1T, showing regolith-like top of tailings; vegetation-rich uppermost part was removed, but spicule-like remnants can be seen at right.

(d) WA-17, C-1B, which underlies (c) and is part of the same core, showing relatively thick oxide-rich (dark) and oxide-poor (light) layers.

(e) WA-17, C-2, showing bedded tailings similar to (d), but gradational to coarser, cross-bedded fraction at bottom.

a
b
c
d
e

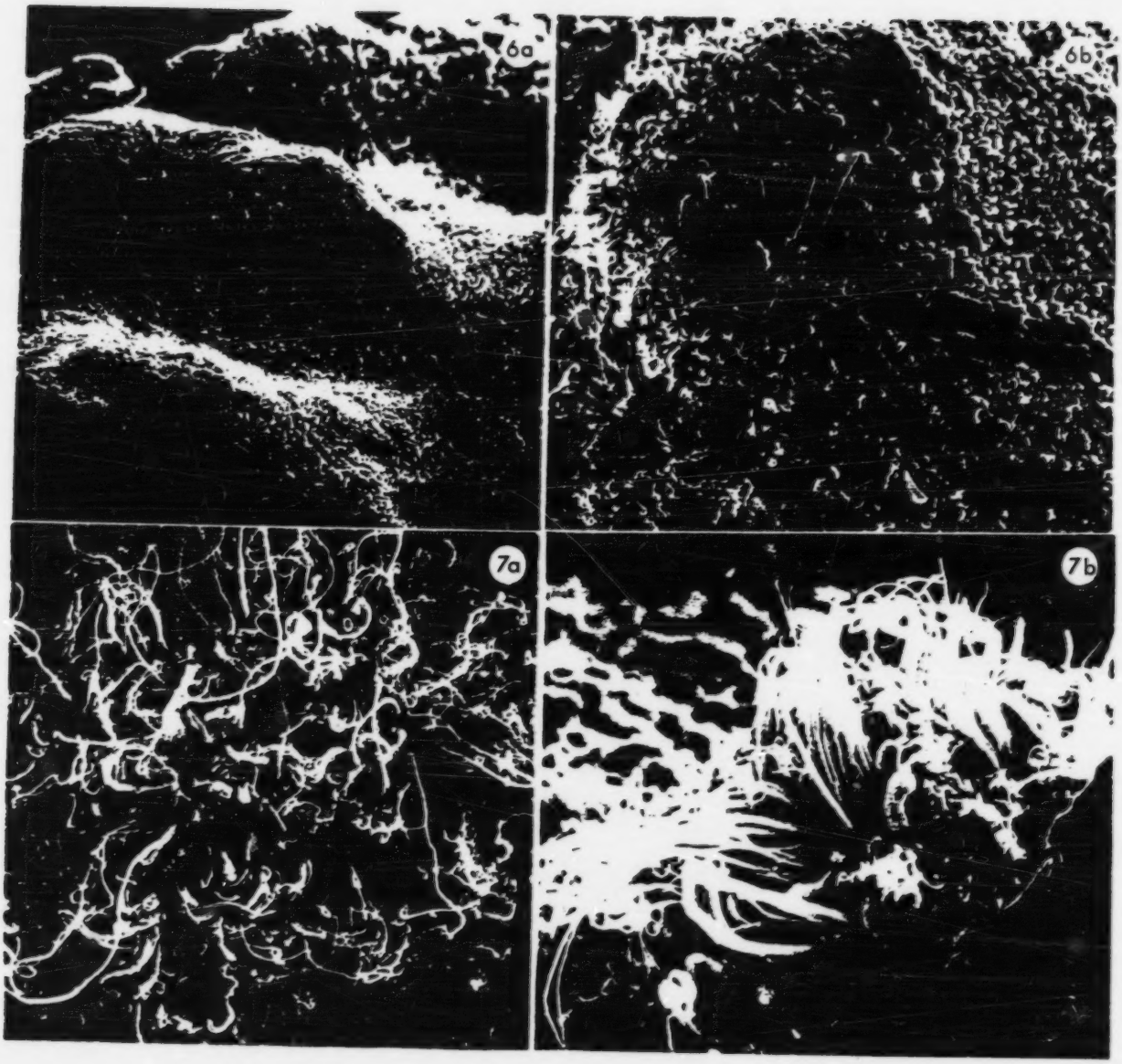

Fig. 6. SEM photographs of (a) radial array of gypsum which crystallized during drying of the core and precipitated on the broken core surface; (b) gypsum rosette from the same sample (WA-8, C-6).

Fig. 7. SEM photographs of filiform magnesian ferrohexahydrite, $(Fe,Mg)SO_4.6H_2O$, formed during drying of core WA-8, C-6. (a) Tangled hair-like mass on core surface; (b) side view showing upright growth from core surface.

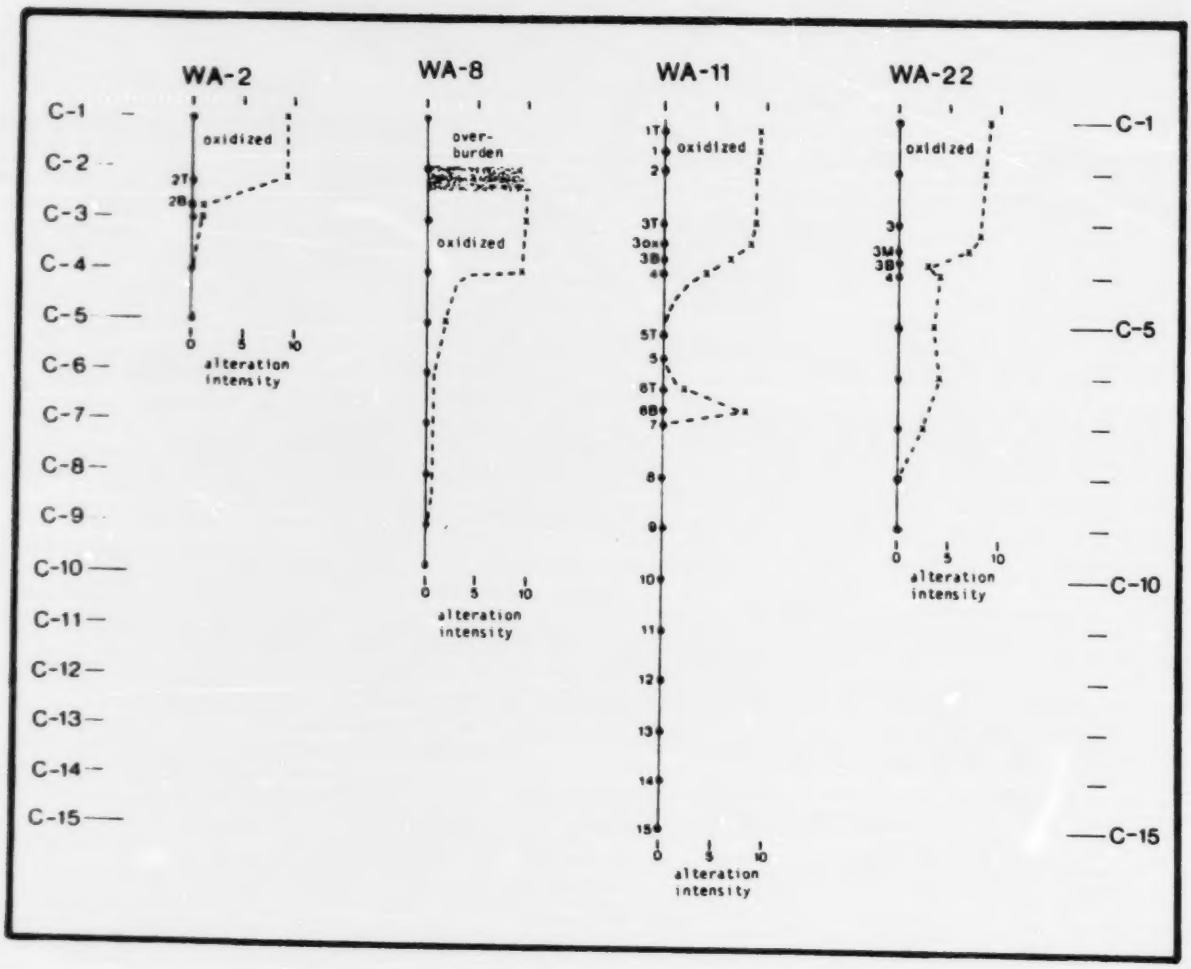

Fig. 8. Alteration intensity of cores from the longitudinal section of the tailings pile (Fig. 2). For Figures 8 to 19, inclusive, the vertical scale is based on sample numbers (C-1 to C-15) because exact sample depths were not provided; dots along borehole length represent relative positions of core samples, and x's indicate intensity of alteration as determined microscopically.

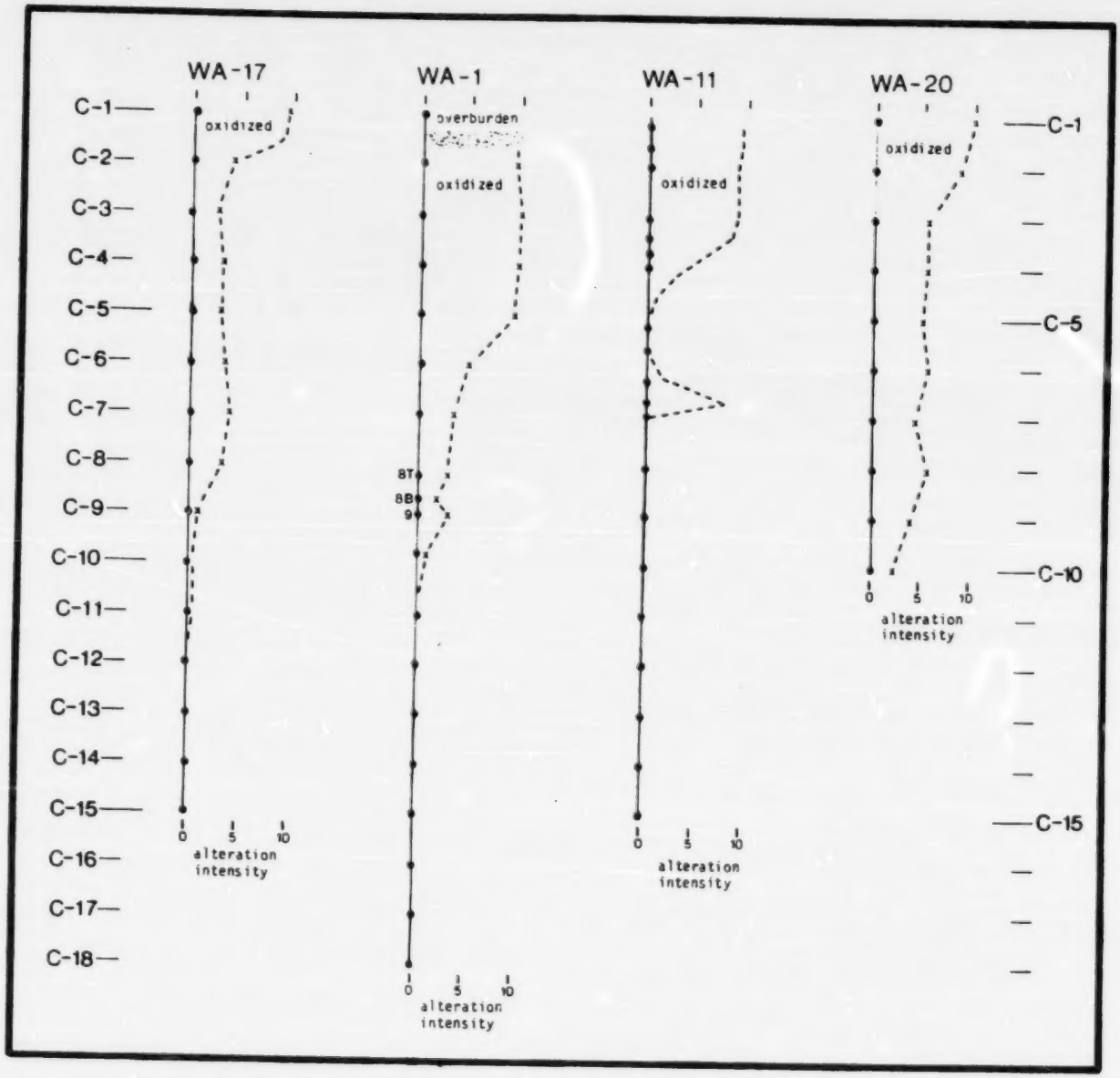

Fig. 9. Microscopically determined alteration intensity in the cross-section of the tailings pile (Fig. 2). Details are explained in the caption for Fig. 8.

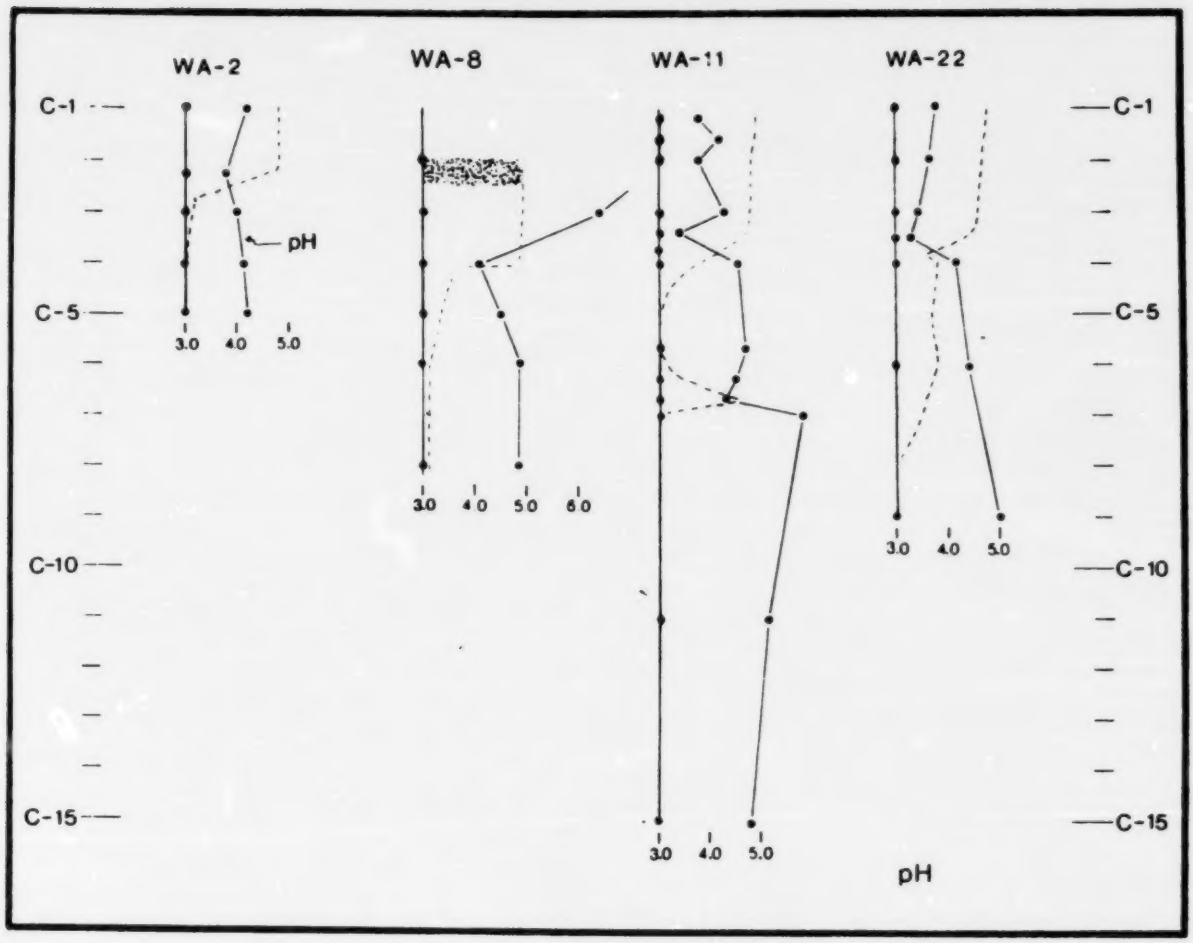

Fig. 10. Variations in pH for the water-soluble fraction in samples from the Waite Amulet longitudinal section. Finely dashed line represents alteration intensity as shown in Figure 8.

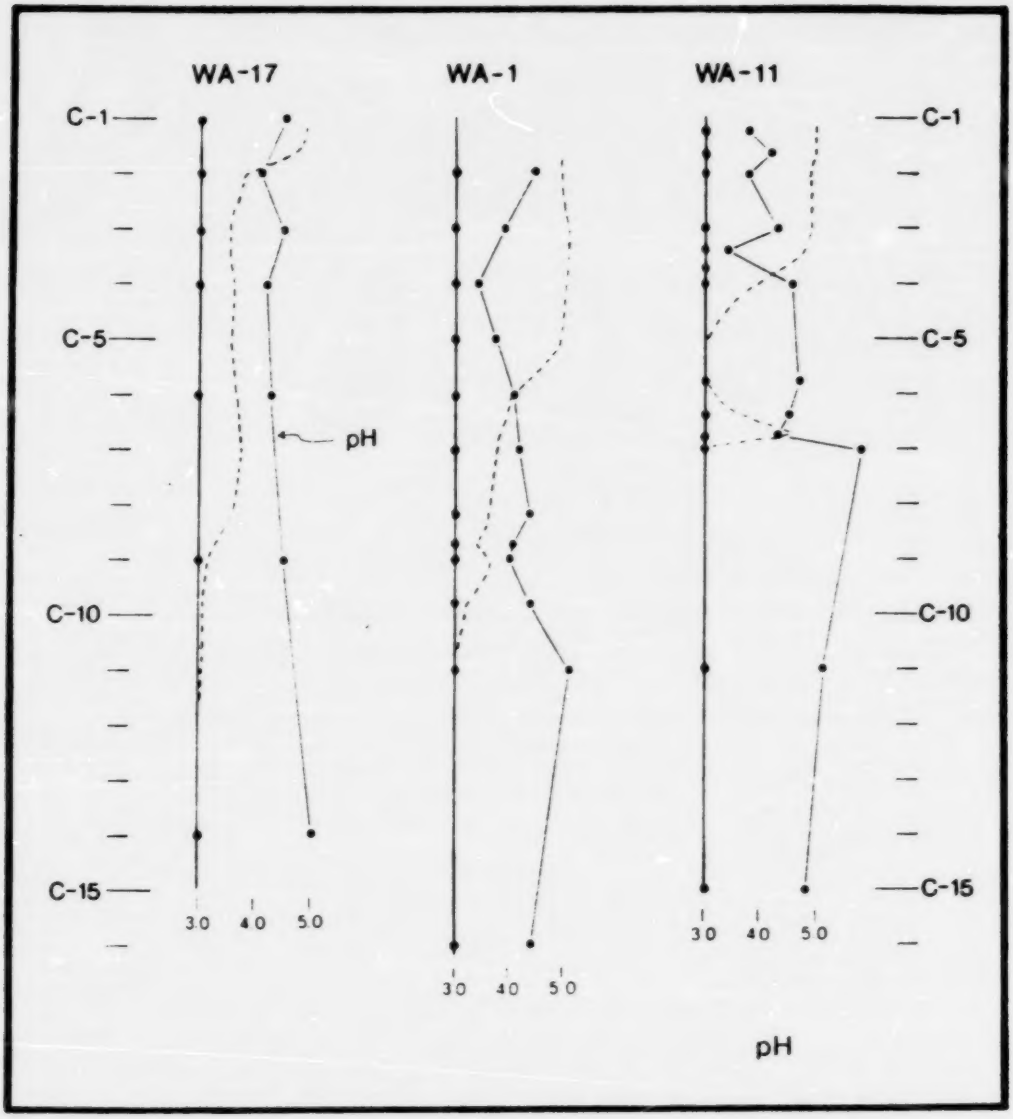

Fig. 11. Variations in pH for the water-soluble fraction in samples from the Waite Amulet cross-section. Finely dashed line represents alteration intensity as shown in Figure 9.

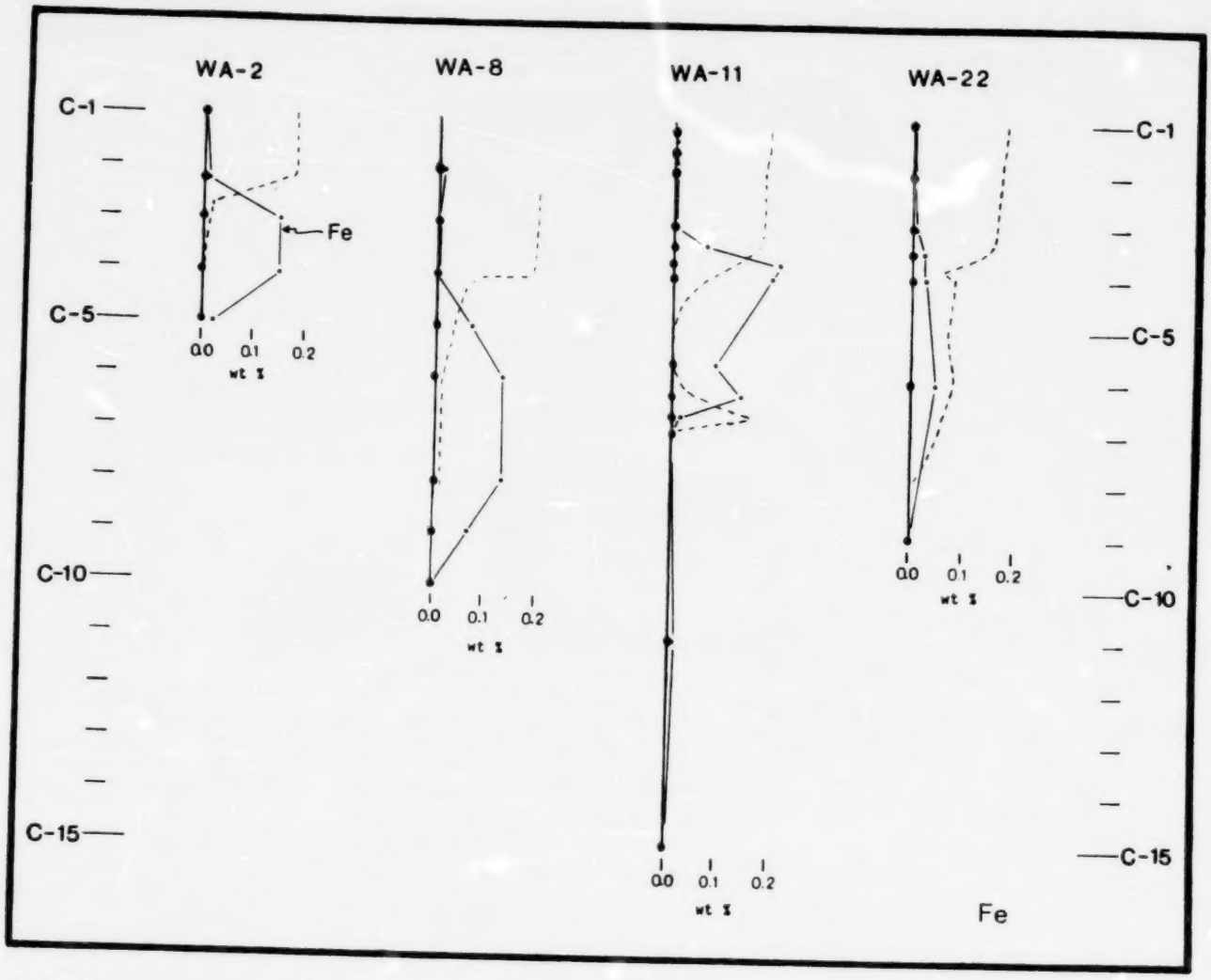

Fig. 12. Variations in wt. % Fe in the water-soluble fraction of samples from the Waite Amulet longitudinal section.

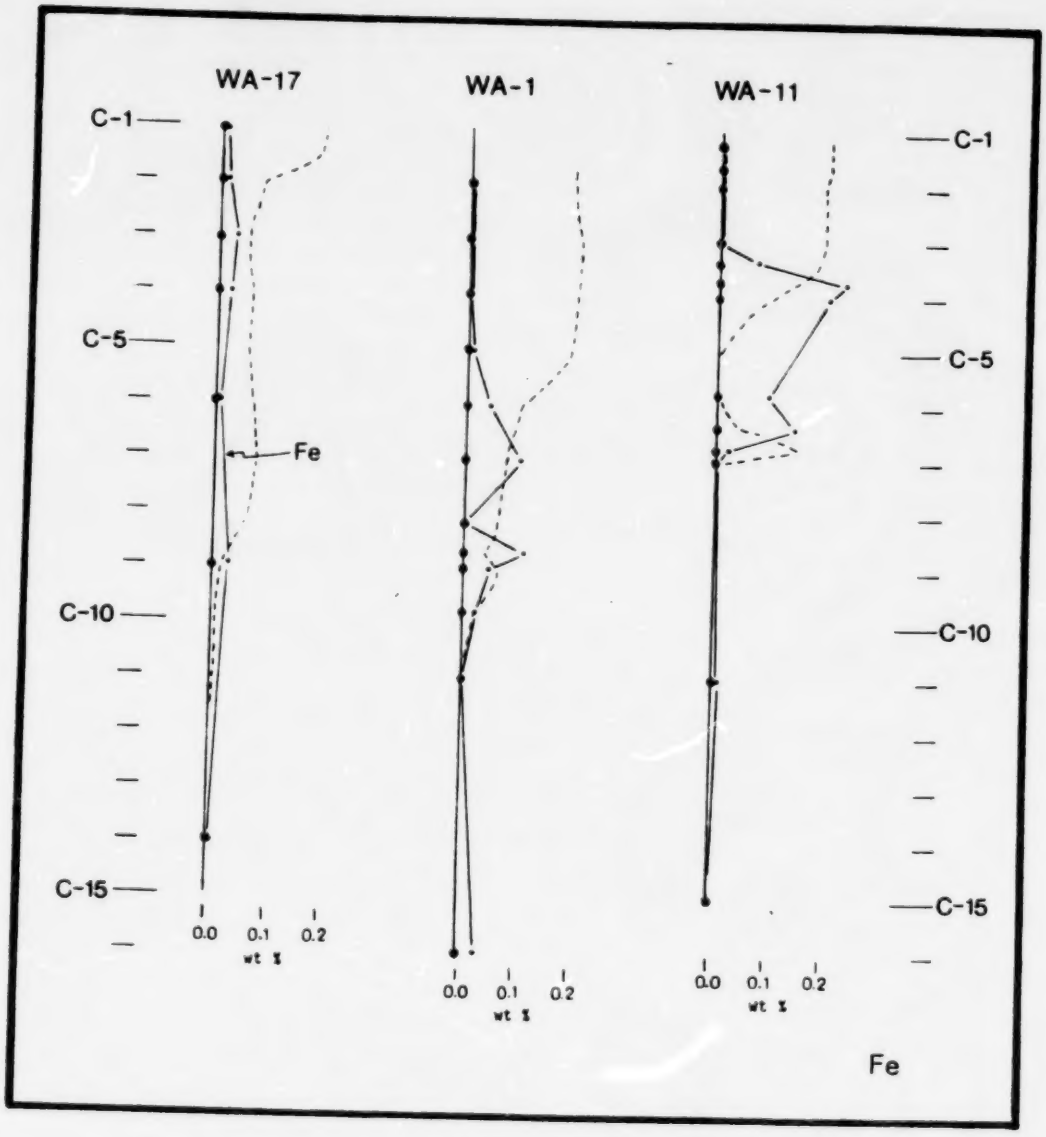

Fig. 13. Variations in wt. % Fe in the water-soluble fraction of samples from the Waite Amulet cross-section.

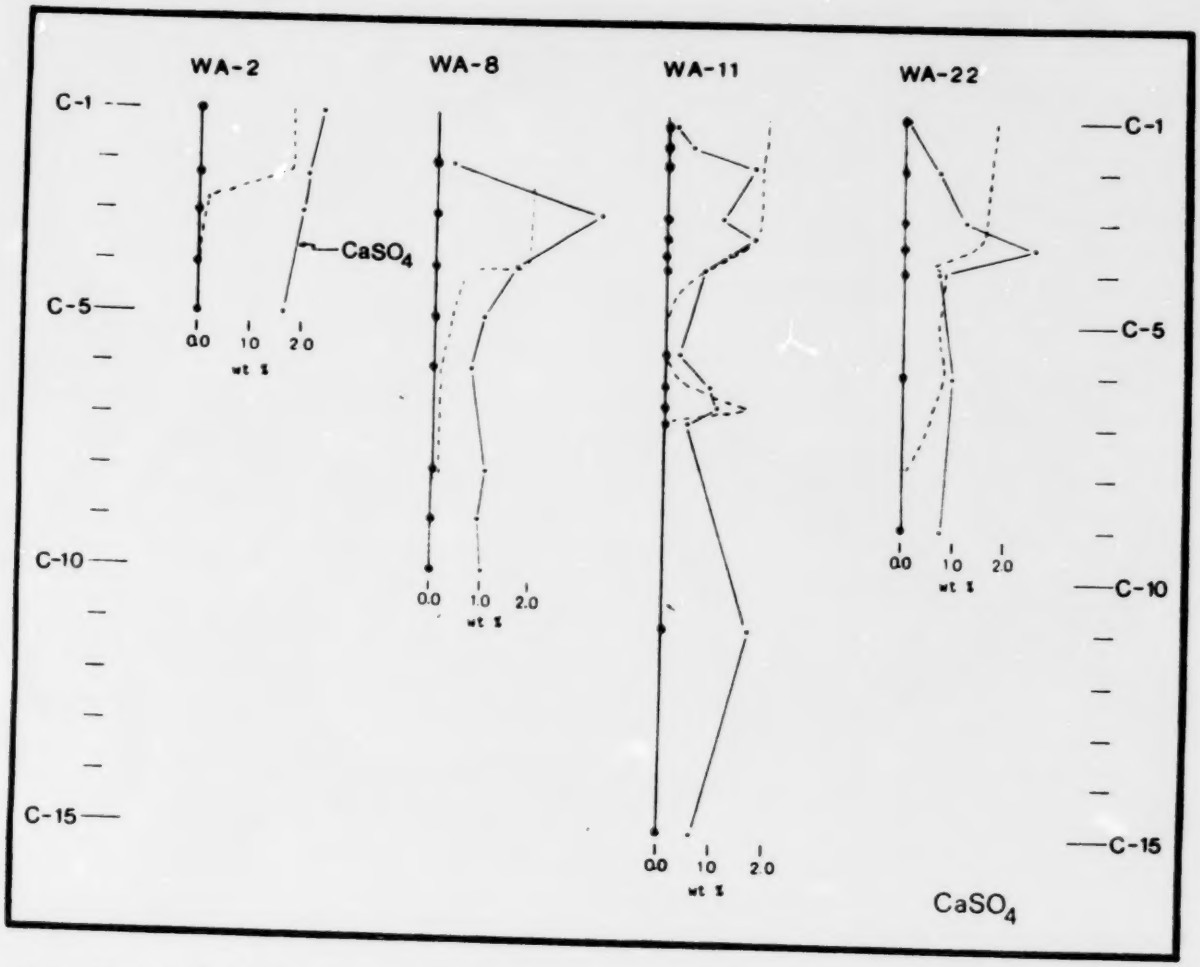

Fig. 14. Variations in wt. % $CaSO_4$ as calculated from Ca contents of the water-soluble fraction in samples from the Waite Amulet longitudinal section.

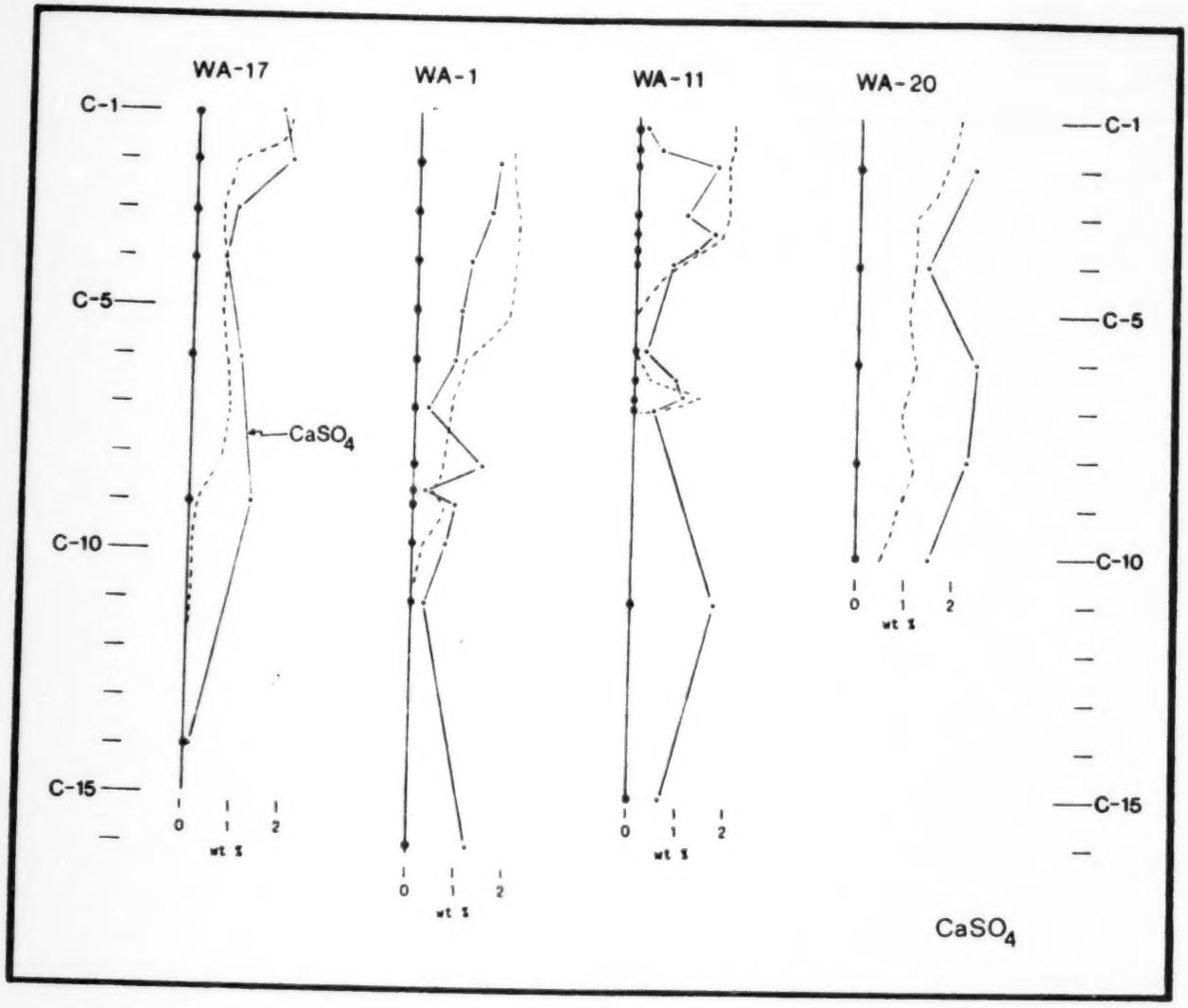

Fig. 15. Variations in wt. % $CaSO_4$ as calculated from Ca contents of the water-soluble fraction in samples from the Waite Amulet cross-section.

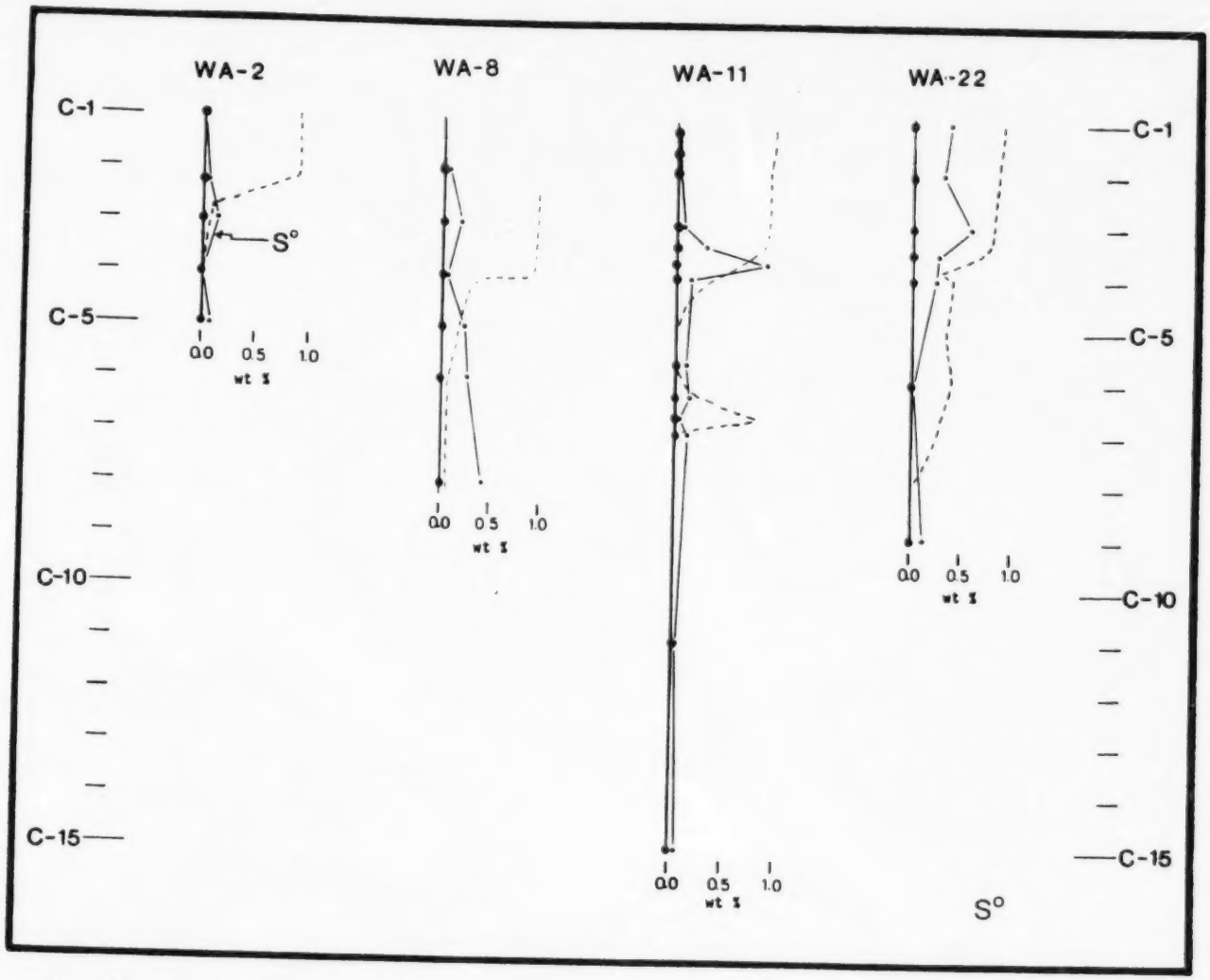

Fig. 16. Variations in wt. % elemental sulphur in samples from the Waite Amulet longitudinal section.

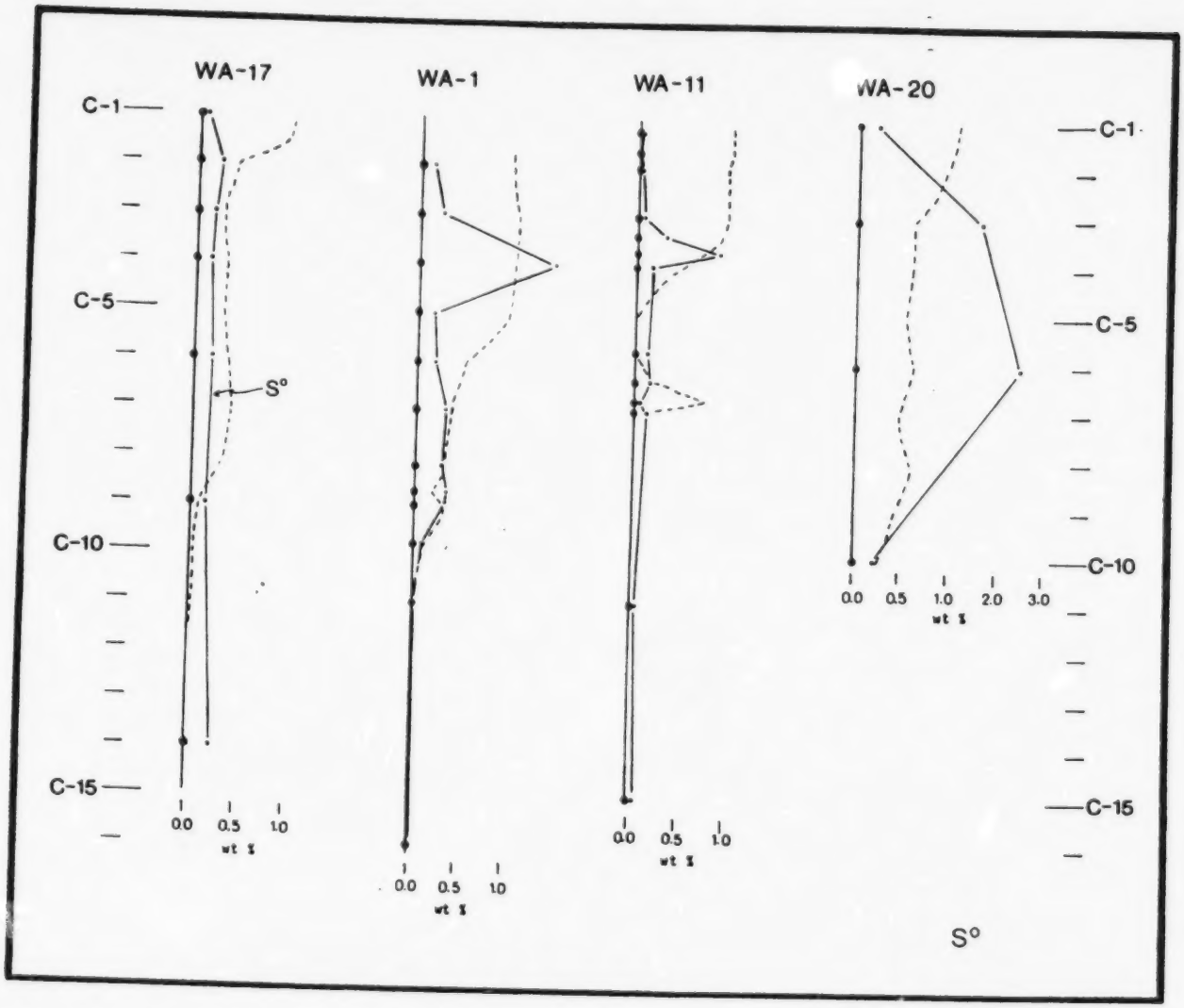

Fig. 17. Variations in wt.% elemental sulphur in samples from the Waite Amulet cross-section.

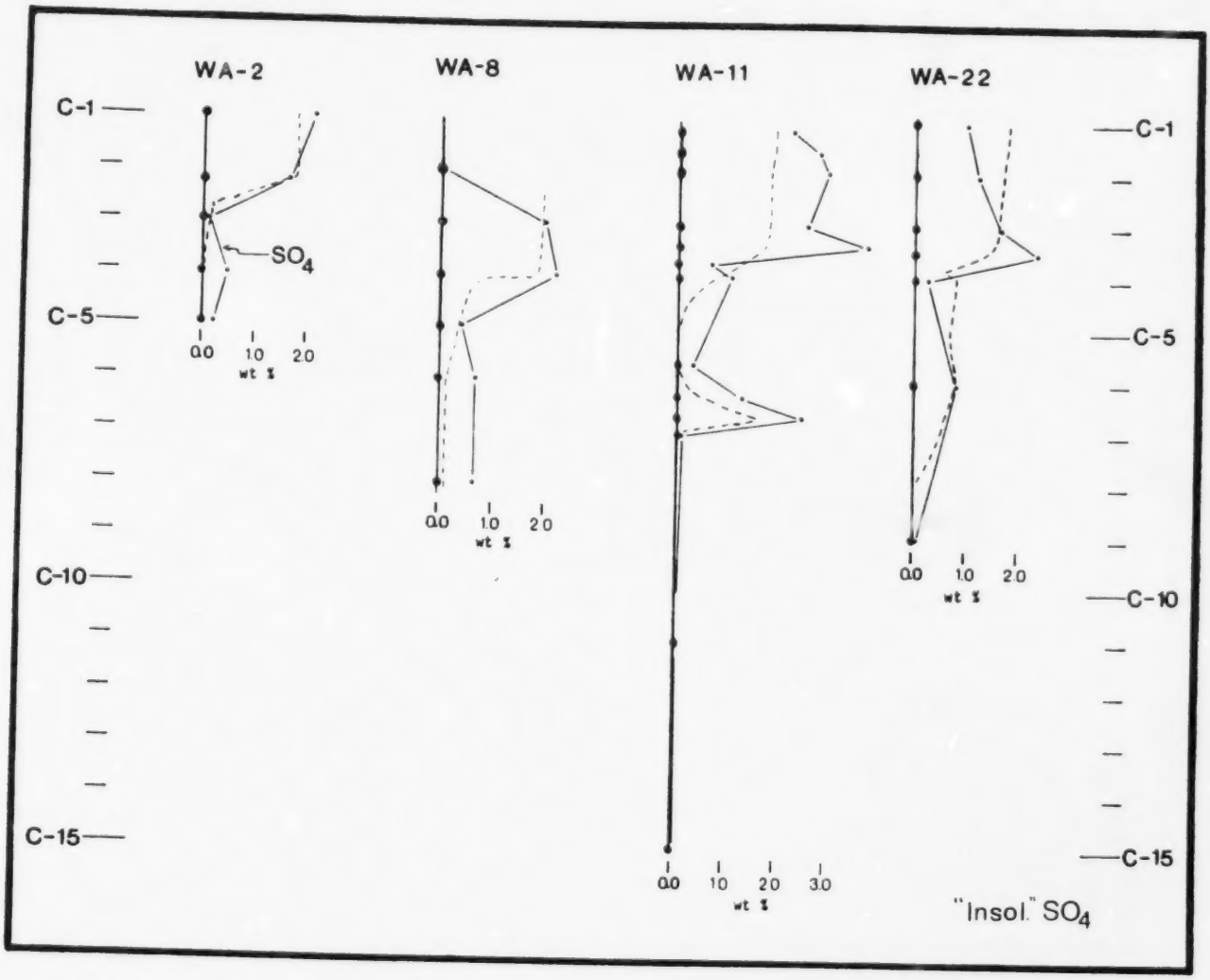

Fig. 18. Variations in SO_4, excluding the water-soluble fraction, in the Waite Amulet longitudinal section. The values basically represent the sulphate that has been precipitated as jarosite.

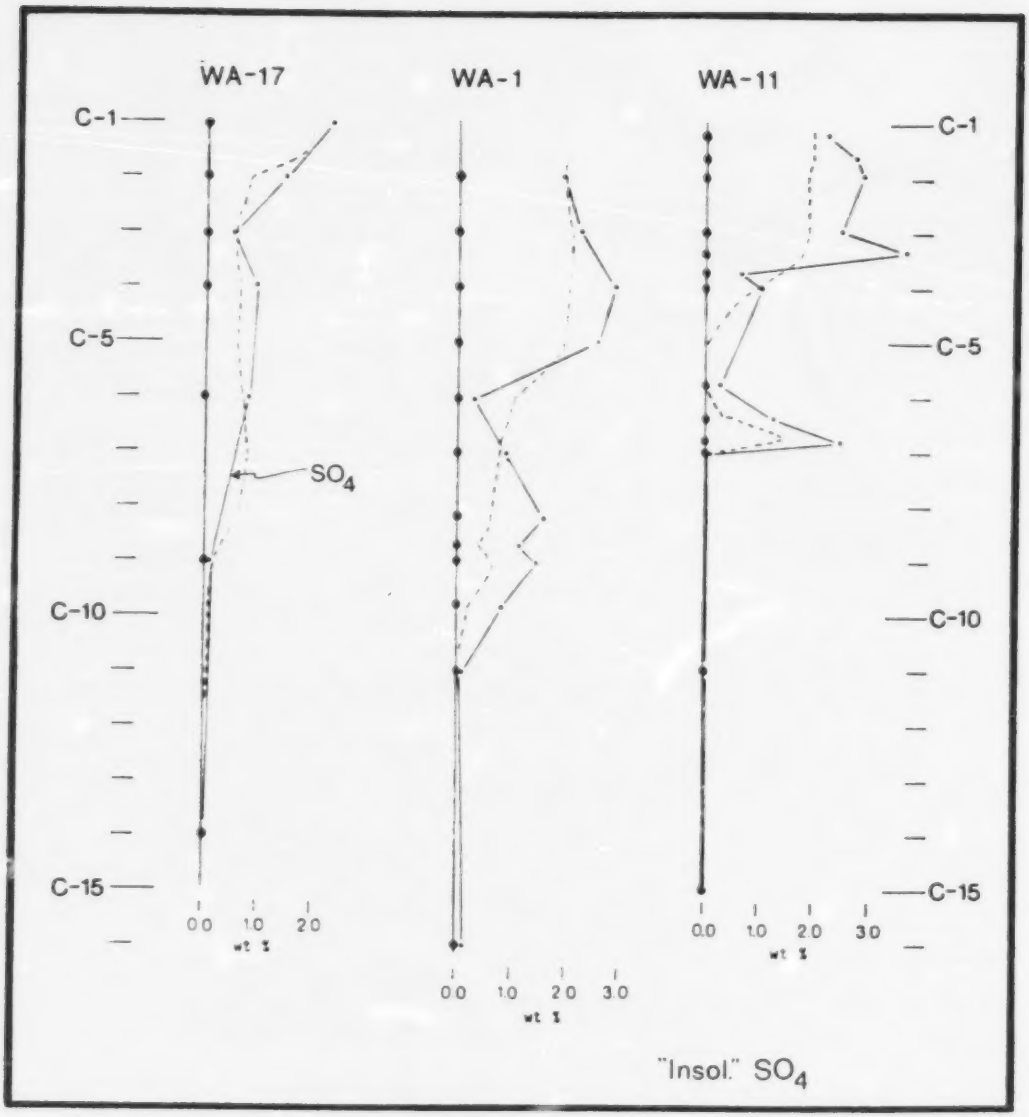

Fig. 19. Variations in SO_4, excluding the water-soluble fraction, in the Waite Amulet cross-section. The values basically represent the sulphate that has been precipitated as jarosite (Fig. 20).

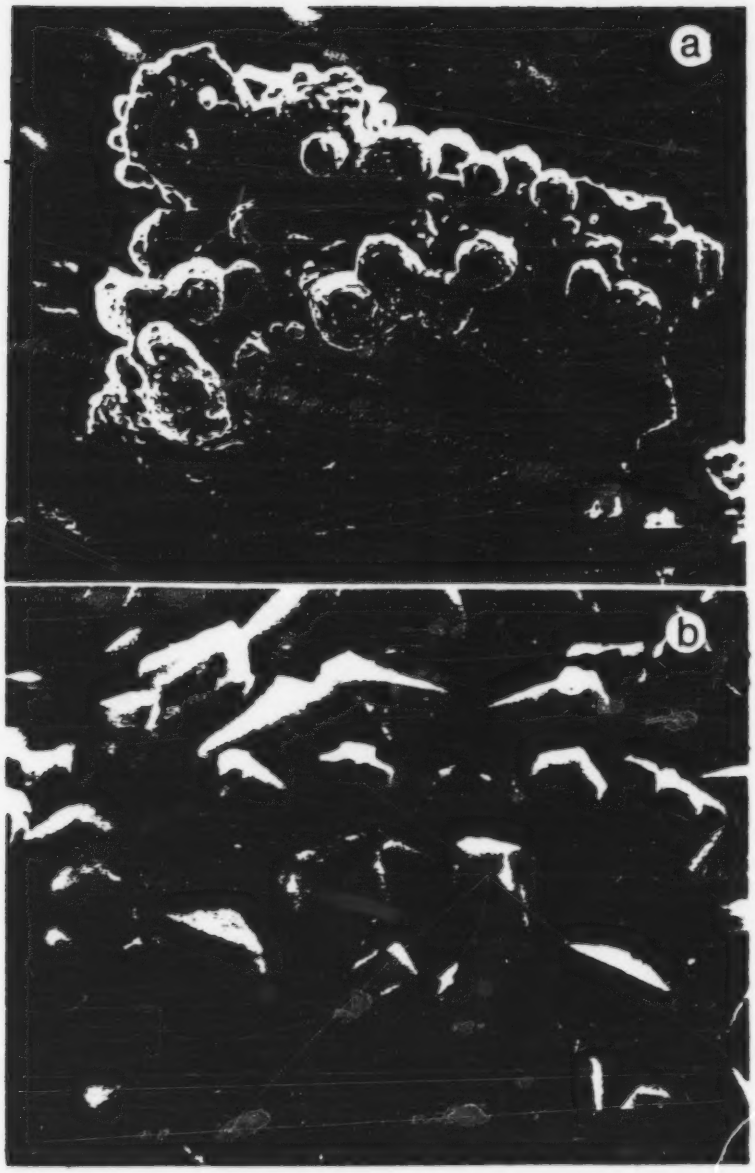

Fig. 20. (a) SEM photograph showing jarosite spheres consisting of fine-grained crystal aggregates; jarosite also occurs in the matrix, cementing the tailings particles. (b) Higher magnification, showing well-formed crystals on the same sample, WA-1, C-4.

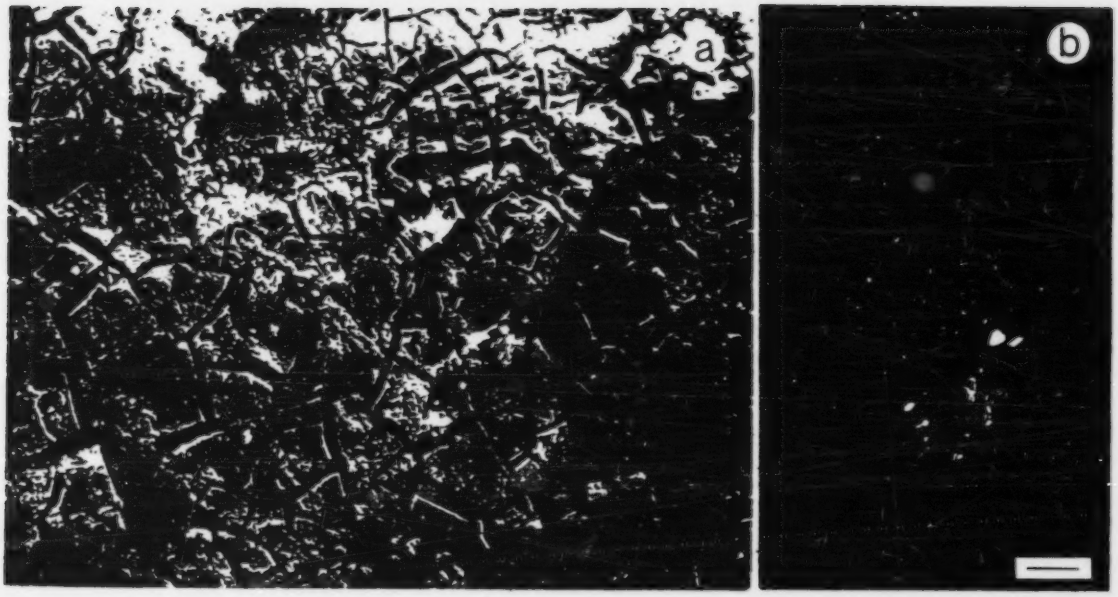

Fig. 21. (a) SEM photograph of ferrihydrite showing "mud-crack" texture characteristic of dehydration. (b) Ferrihydrite capping on a tailings clump; polished section, reflected light; bar scale represents 0.05 mm. Both photos are of sample WA-3, C-2T.

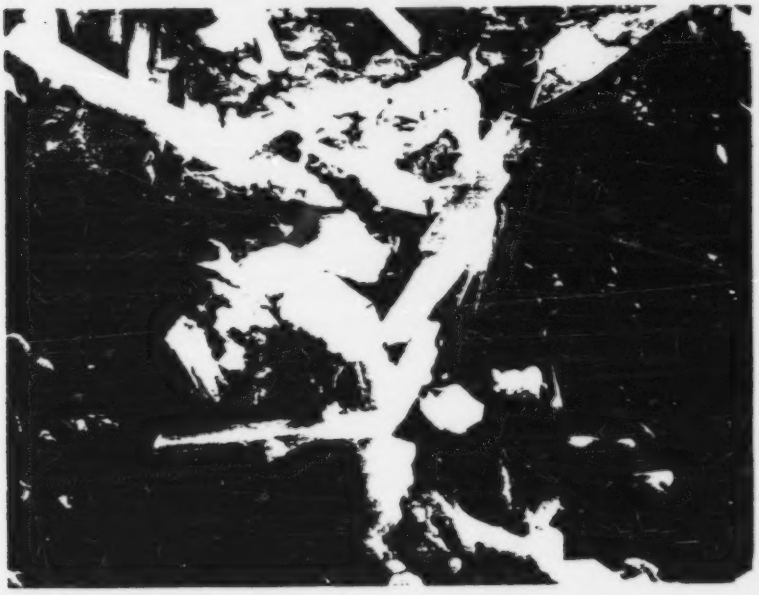

Fig. 22. SEM photograph of euhedral, elongate crystals of unidentified Ca-Fe sulphate mineral associated with anhedral gypsum in sample WA-11, C-3.